



**FACULTY OF MECHANICAL AND CIVIL ENGINEERING KRALJEVO
UNIVERSITY OF KRAGUJEVAC
KRALJEVO – SERBIA**

THE NINTH INTERNATIONAL TRIENNIAL CONFERENCE

HEAVY MACHINERY HM 2017

PROCEEDINGS

ORGANIZATION SUPPORTED BY:

Ministry of Education, Science and Technological Development

Development Agency of Serbia

Zlatibor, June 28 – July 1 2017



PUBLISHER:

Faculty of Mechanical and Civil Engineering, Kraljevo

EDITORS:

Prof. dr Milomir Gašić, mech. eng.

PRINTOUT:

SaTCIP d.o.o. Vrnjacka Banja

TECHNICAL COMMITTEE

dr Vladimir Stojanović
Jovana Bojković
Goran Bošković
Marina Bošković
Vladimir Đorđević
Vladan Grković
Vladimir Mandić
Saša Marinković
Aleksandar Nikolić
Marko Nikolić
Nenad Stojić
Slobodan Todosijević
Jelena Tomić
Slobodan Bukarica
Bojan Beloica

No. of copies: 100

REVIEWS:

All papers have been reviewed by members of scientific committee



CONFERENCE CHAIRMAN

Prof. dr Milomir Gašić, FMCE Kraljevo

INTERNATIONAL SCIENTIFIC PROGRAM COMMITTEE

CHAIRMAN

Prof. Dr Mile Savković, FMCE Kraljevo

VICE-CHAIRMAN

Prof. Dr Milan Kolarević, FMCE Kraljevo, Serbia

MEMBERS

1. Prof. Dr M. Alamoreanu, TU Bucharest, Romania
2. Prof. Dr S. Arsovski, FME Kragujevac, Serbia
3. Prof. Dr D. Atmadzhova, VTU "Todor Kableshev", Sofia, Bulgaria
4. Prof. Dr M. Berg, Royal Institut of Technology-KTH, Sweden
5. Prof. Dr H. Bogdevicius, Technical University, Vilnius, Lithuania
6. Prof. Dr S. Bošnjak, FME Belgrade, Serbia
7. Prof. Dr A. Bruja, TU Bucharest, Romania
8. Prof. Dr Z. Bučevac, FME Belgrade, Serbia
9. Prof. Dr R. Bulatović, FMCE Kraljevo, Serbia
10. Prof. Dr A. Bukvić, FME East Sarajevo, Bosnia and Herzegovina
11. Prof. Dr S. Ćirić-Kostić, FMCE Kraljevo, Serbia
12. Prof. Dr M. Dedić, FMCE Kraljevo, Serbia
13. Prof. Dr R. Durković, FME Podgorica, Montenegro
14. Prof. Dr M. Đapić, FMCE Kraljevo, Serbia
15. Prof. Dr Z. Đinović, Integrated MicroSystem, Vienna, Austria
16. Prof. Dr K. Ehmann, Northwestern University, Chicago, USA
17. Prof Dr O. Erić, FMCE Kraljevo, Serbia
18. Prof. Dr A. Emeljanova, HGTUSA Harkov, Ukraine
19. Prof. Dr V. Filipović, FMCE Kraljevo, Serbia
20. Prof. Dr G. Minak, University of Bologna, Italy
21. Prof. Dr M. Gagl, Integrated MicroSystem, Vienna, Austria
22. Prof. Dr D. Golubović, FME East Sarajevo, Bosnia and Herzegovina
23. Prof. Dr V. Jovišević, FME Banja Luka, Bosnia and Herzegovina
24. Prof. Dr B. Jerman, FME Ljubljana, Slovenia
25. Prof. Dr Z. Jugović, Tehnical Faculty Čačak, Serbia
26. Prof. Dr V. Karamarković, FMCE Kraljevo, Serbia
27. Prof Dr R. Karamarković, FMCE Kraljevo, Serbia
28. Prof. Dr M. Karasahin, Demirel Univerity, Istanbul, Turkey
29. Prof. Dr I. Kiričenko, HNADU Kiev, Ukraine
30. Prof. Dr K. Kocman, Tecnical University of Brno, Czech Republic
31. Prof. Dr S. Kolaković, Faculty of Tehnical Sciences, Novi Sad, Serbia
32. Prof. Dr M. Kostic, Northern Illinois University, DeKalb, USA
33. Prof. Dr M. Králik, FME Bratislava, Slovakia



34. Prof. Dr E. Kudrjavcev, MGSU, Moscow, Russia
35. Prof. Dr Đ. Lađinović, Faculty of Tehnical Sciences, Novi Sad, Serbia
36. Prof. Dr LJ. Lukić, FMCE Kraljevo, Serbia
37. Prof. Dr Z. Marinković, FME Niš, Serbia
38. Prof. Dr N. Mešćerin, MGSU, Moscow, Russia
39. Prof. Dr N. Nedić, FMCE Kraljevo, Serbia
40. Prof. Dr N. Nenov, VTU “Todor Kableskov”, Sofia, Bulgaria
41. Prof. Dr V. Nikolić, FME Niš, Serbia
42. Prof. Dr E. Nikolov, Technical University, Sofia, Bulgaria
43. Prof. Dr M. Ognjanović, FME Belgrade, Serbia
44. Prof. Dr J. Peterka, FMS&T, Trnava, Slovakia
45. Prof. Dr D. Petrović, FMCE Kraljevo, Serbia
46. Prof. Dr J. Polajnar, BC University, Prince George, Canada
47. Prof. Dr D. Pršić, FMCE Kraljevo, Serbia
48. Prof. Dr V. Radonjanin, Faculty of Tehnical Sciences, Novi Sad, Serbia
49. Prof. Dr V. Raičević, FME Kosovska Mitrovica, Serbia
50. Prof. Dr M. Rajović, FMCE Kraljevo, Serbia
51. Prof. Dr M. Stefanović, FME Kragujevac, Serbia
52. Prof. Dr D. Sever, Maribor, Civil Engineering, Slovenia
53. Prof. Dr M. A. Stepanov, MGSU, Moscow, Russia
54. Prof. Dr I. S. Surovcev, VGSU, Voronezh, Russia
55. Prof. Dr S. Šalinić, FMCE Kraljevo, Serbia
56. Prof. Dr Z. Šoškić, FMCE Kraljevo, Serbia
57. Prof. Dr LJ. Tanović, FME Belgrade, Serbia
58. Prof. Dr S. Trifunović, FMCE Kraljevo, Serbia
59. Prof. Dr J. Vladić, Faculty of Tehnical Sciences, Novi Sad, Serbia
60. Prof. Dr M. Vukićević, FMCE Kraljevo, Serbia
61. Prof. Dr K. Weinert, University of Dortmund, Germany
62. Prof. Dr N. Zrnić, FME Belgrade, Serbia

ORGANIZING COMMITTEE

CHAIRMAN:

Prof. Dr Ljubomir Lukić, FMCE Kraljevo

VICE-CHAIRMAN:

Prof. Dr Zlatan Šoškić, FMCE Kraljevo, Serbia

MEMBERS:

Doc. Dr Lj. Dubonjić, FMCE Kraljevo, Serbia
Doc. Dr M. Bižić, FMCE Kraljevo, Serbia
Doc. Dr M. Bjelić, FMCE Kraljevo, Serbia
Doc. Dr N. Bogojević, FMCE Kraljevo, Serbia
Doc. Dr M. Ljujić, FMCE Kraljevo, Serbia
Doc. Dr M. Marašević, FMCE Kraljevo, Serbia

Doc. Dr G. Marković, FMCE Kraljevo, Serbia
M.A. N. Pavlović, FMCE Kraljevo, Serbia
Doc. Dr A. Petrović, FMCE Kraljevo, Serbia
Doc. Dr B. Radičević, FMCE Kraljevo, Serbia
Doc. Dr N. Zdravković, FMCE Kraljevo, Serbia



PREFACE

Ladies and gentlemen, dear colleagues,

Welcome to Zlatibor, to the International Scientific Conference Heavy Machinery 2017.

This year the International Conference Heavy Machinery is held by the University of Kragujevac, Faculty of Mechanical and Civil Engineering in Kraljevo from 28 of June to 1 of July 2017.

It has gained a unique recognizable form for exchange of information, ideas and new scientific researches. The Conference is held in the year when the Faculty of Mechanical and Civil Engineering in Kraljevo celebrates the 58th year of university teaching in mechanical engineering and sixth year of university teaching in civil engineering.

For 24 years of its existence it has acquired specific and recognizable form in domestic and foreign scientific circles thanks to its scientific and research results.

The goal of the Conference is to make the research from the fields covered at the Faculty of Mechanical and Civil Engineering in Kraljevo available and applicable both within domestic and foreign frames. Also, our scientific workers will have the opportunity to learn about results of research done by their colleagues from abroad in the fields of transport design in industry, energy control, production technologies, and civil engineering through the following thematic sessions:

- Earth moving and transportation machinery,
- Production technologies,
- Automatic control, robotics and fluid technique,
- Machine design and mechanics,
- Railway engineering,
- Thermal technique and environment protection,
- Civil engineering and materials.

High scientific rating of domestic and foreign participants as well as the number of papers provide guarantees that the Conference is going to be very successful.

I wish to emphasize that this year we have a large number of papers, especially from abroad. The program also contains 104 invited papers in the plenary session. The invited lectures reflect the wide spectrum of important topics of current interest in heavy machinery. The sponsorship by the Ministry of Education and Science of the Republic of Serbia is supportive of efforts to promote science and technology in the area of mechanical and civil engineering in Serbia. We would like to express our sincere thanks to all members of scientific and organizing committee, reviewers, as well as to all participants including invited speakers for coming to Zlatibor to present their papers.

Thank you and see you at the next conference.

Kraljevo – Zlatibor, June 2017

Conference Chairman,


Prof. Dr. Milomir Gašić, mech eng.

PLENARY SESSION

COMPUTER MODELLING OF A DIGGING ZONE OF A SINGLE-BUCKET EXCAVATOR Evgeniy M. Kudryavtsev	1
AN EXPERIMENTAL STUDY ON THE FATIGUE RESPONSE OF 15-5 PH STAINLESS STEEL BUILT BY DMLS Dario Croccolo, Massimiliano De Agostinis, Stefano Fini, Giorgio Olmi, Aleksandar Vranic, Snezana Ciric-Kostic	9
TRIBOLOGICAL PROPERTIES OF DETERGENTS AS ADDITIVES FOR MOTOR OILS Anatoly Dotsenko, Vladimir Samusenko	17
A SURVEY OF RESEARCHES IN THE FIELD OF ECODESIGN RELATED TO INTRALOGISTICS AT THE UNIVERSITY OF BELGRADE - FACULTY OF MECHANICAL ENGINEERING (2010-2017) Nenad Zrnić	23
DAMPING CHARACTERISTICS OF THE SEISMIC ISOLATION BEARINGS GROUP, IN MODULAR DESIGN, FOR BRIDGES AND VIADUCTS Marian Dima, Catalin Francu	41

SESSION A: EARTH-MOVING AND TRANSPORTATION MACHINERY

DYNAMIC ANALYSIS OF TOWER CRANE MOVEMENT MECHANISM Evgeniy Kudryavtsev	1
THE DEFINITION OF BASIC PARAMETERS OF THE SET OF SMALL-SIZED EQUIPMENT FOR PREPARATION OF DRY MORTAR FOR VARIOUS APPLICATIONS Inga Emelyanova, Vladimir Blazhko, S.I Karpenko	7
SHAPELESS MANUFACTURE OF REINFORCED CONCRETE CYLINDRICAL AND SPHERICAL SHELLS WITH THE HELP OF NEW GENERATION HYDRAULIC EQUIPMENT OF NEW GENERATIONS Inga Emelyanova, Ana Anishchenko, Sergey Guzenko, Denis Chayka	11
RESEARCH OF STRESS-STRAIN STATE OF METAL CONSTRUCTIONS FOR STATIC AND DYNAMIC LOADS MACHINERY Ivan Nazarenko, Oleg Dedov, Igor Zalisko	17
RESEARCH OF ENERGY-SAVING VIBRATION MACHINES WITH ACCOUNT OF THE STRESS-STRAIN STATE OF TECHNOLOGICAL ENVIRONMENT Ivan Nazarenko, Oleg Dedov, Anatoly Svidersky, Nicolay Ruchinsky	21
APPLICATION OF NUMERICAL METHODS FOR ANALYSIS OF VERTICAL TRANSPORT SYSTEMS Jovan Vladić, Radomir Đokić, Anto Gajić	25
GEOMETRICAL IDENTIFICATION OF CYLINDRICAL CARRIER OF AXIAL BEARINGS WITH BIG DIAMETERS Milomir Gašić, Mile Savković, Goran Marković, Nebojša Zdravković, Srđan Ribar	33

DESIGN OPTIMIZATION OF THE RECTANGULAR BOX SECTION OF THE DOUBLE BEAM BRIDGE CRANE USING MATLAB OPTIMIZATION TOOLBOX	37
Goran Pavlović, Mile Savković, Nebojša Zdravković, Vladimir Kvrđić, Stefan Mitrović	
INTEGRITY OF BEAM BRACES AND THREADED SPINDLE FOR CONJOINT OPERATION OF TWO 5 MN BRIDGE CRANES	45
Miodrag Arsić, Mladen Mladenović, Bojan Međo, Zoranka Malešević, Zoran Savić	
ORGANIZATIONAL-TECHNOLOGICAL MODELS FOR THE FORMATION OF EFFECTIVE SETS OF MACHINES AND TECHNOLOGIES IN THE PERFORMANCE OF CONSTRUCTION WORKS	53
Maxim Nazarenko, Ivan Pereginets, Viktor Leschinsky	
RISK MANAGEMENT IN MECHANICAL ENGINEERING	57
Vladimir Zorin	
LABORATORY TEST RIG FOR NONDESTRUCTIVE INSPECTION OF STEEL CORD BELTS	61
Miloš Đorđević, Nenad Zrnić, Srđan Bošnjak	
ANALYSIS OF THE INFLUENCE OF BASIC PARAMETERS OF THE MAGNETIC SEPARATOR ECMS-500 FOR NON-FERROUS METALS ON THE SEPARATION FORCE INTENSITY	69
Mile Savković, Milomir Gašić, Nebojša Zdravković, Goran Marković, Goran Pavlović	
APPLICATION OF RELIABILITY CENTERED MAINTENANCE METHODOLOGY FOR MAINTENANCE OF AN SPECIAL MILITARY VEHICLE ENGINE	75
Slavko Rakić, Uglješa Bugarić	
THE APPLICATION OF VOITH HYDRODYNAMIC COUPLERS WHILE STARTING THE BELT CONVEYORS OF MINING	83
Dragoljub Veličković, Svetislav Marković, Dragana Andjelić	
SOME MODERN SOLUTIONS FOR DELIVERY OPERATION IN POSTAL TRAFFIC	87
Aleksandar Čupić, Mladenka Blagojević, Goran Marković	
MATERIAL HANDLING EQUIPMENT SELECTION USING AN INTEGRATED APPROACH F-MODIPROM: AN ADVANTAGE GAINED FROM USING FUZZY NUMBERS	95
Goran Marković, Mile Savković, Nebojša Zdravković, Aleksandar Čupić, Marko Popović	
DIGGING RESISTANCE MODEL SHOVEL MANIPULATOR OF HYDRAULIC EXCAVATOR	101
Vesna Jovanović, Dragoslav Janošević, Jovan Pavlović, Goran Petrović	
ANALYSIS OF THE INFLUENCE OF PARAMETERS OF HYDROSTATIC SYSTEM ON THE MANIPULATOR DRIVE OF THE MOBILE MACHINE	105
Jovan Pavlović, Dragoslav Janošević, Vesna Jovanović, Nikola Petrović	
RESEARCH AND CALCULATION OF RATIONAL MODES AND PARAMETERS OF AN ULTRASONIC CAVITATOR	109
Irina Bernyk, Oleksandr Lugovskoy	

SESSION B: PRODUCTION TECHNOLOGIES

DETERMINATION OF EXPULSION COSTS IN RESISTANCE SPOT WELDING	1
Miomir Vukićević, Mišo Bjelić, Marina Pljakić, Milan Tešević	

NUMERICAL SIMULATION OF HARDNESS DISTRIBUTION AT THE HAZ OF P355GH STEEL Mišo Bjelić, Karel Kovanda, Ladislav Kolařík, Marie Kolaříková, Miomir Vukićević, Branko Radičević	7
APPLICATION OF MULTICRITERIA DECISION MAKING IN SELECTION OF OPTIMAL TOOLPATH Aleksandra Petrović, Slobodan Ivanović, Goran Miodragović, Vladan Grković	13
ELECTRODE INVESTIGATION AT PLASMA CUTTING Bogdan Nedić, Marko Jankovic, Peko Ivan	19
ANALYTICAL ANALYSIS OF DRILLING-ASSOCIATED DAMAGE IN COMPOSITES Navid Zarif Karimi, Giangiacomo Minak	23
THE SIMULATION PROCESS IN SMALL AND MEDIUM ENTERPRISES: DECISION-MAKING SUPPORT Miroslav Dragić, Miloš Sorak	29
THE INFLUENCE OF WORKING EXPERIENCE AND LEVEL OF EDUCATION ON THE MARKET ORIENTATION OF SMES IN TRANSITION Ljiljana Pecić, Milan Kolarević, Vladan Grković, Natasa Obradović	37
ESSENTIAL REQUIREMENTS FOR SUSTAINABILITY COMPLIANCE IN THE PROCESS OF EXPLOITATION MACHINES Miljan Cvetković, Žarko Janković, Dragan Cvetković	45
PARTNERSHIP FOR ENTREPRENEURIAL ENGINEERING EDUCATION Milica Gerasimović, Ugljesa Bugarić	51
ORAL PRESENTATIONS OF COMPANIES IN ESP CLASSES AS A MULTI-PURPOSE TASK Nataša Pavlović	55
MACHINING SIMULATION AND VERIFICATION OF TOOL PATH FOR CNC MACHINE TOOLS WITH SERIAL AND HYBRID KINEMATICS Saša Živanović, Slobodan Tabaković, Milan Zeljković, Cvijetin Mladenović, Aleksandar Košarac	63
3D ANIMATION OF WORKPIECE TRANSFORMATION DURING MILLING OPERATION Slobodan Ivanović, Aleksandra Petrović, Ljubomir Lukić, Marina Pljakić	69
OPTIMIZATION MODEL FOR MACHINING PROCESSES DESIGN IN FLEXIBLE MANUFACTURING SYSTEMS Ljubomir Lukic, Slobodan Ivanovic, Aleksandra Petrovic, Mirko Djapic	75
APPLICATION OF AXIOMATIC DESIGN THEORY AND BELIEF FUNCTION THEORU IN THE ASSEMBLY SYSTEM IMPROVEMENT Zvonko Petrović, Mirko Đapić, Ljubomir Lukić	83
THE APPLICATION OF DEMPSTER-SHAFER THEORY ON FAILURE ANALYSIS OF HYDRAULIC HAND PUMPS Violeta Đorđević, Mirko Đapić, Zvonko Petrović	89

REMOTE MONITORING AND CONTROL OF ASYNCHRONOUS DRIVES PERFORMANCE – LABORATORY STAND Vasil Dimitrov, Petko Kostadinov	97
SYNERGISTIC MODEL OF TRAFFIC FLOWS Galina Cherneva, Emiliya Dimitrova	103
DYNAMIC FAULT TREE. COMPUTATION OF PARAMETERS – PART I Emiliya Dimitrova, Plamen Atanasov	109
DYNAMIC FAULT TREE. COMPUTATION OF PARAMETERS – PART II Emiliya Dimitrova, Plamen Atanasov	115
SESSION C: AUTOMATIC CONTROL, ROBOTICS AND FLUID TECHNIQUE	
ADAPTIVE INPUT DESIGN FOR ROBUST IDENTIFICATION OF OUTPUT-CONSTRAINED OE MODELS Vladimir Stojanović, Novak Nedić, Dragan Pršić	1
CONDITIONAL OPTIMIZATION OF COMPUTER AUTOMATIC CONTROL SYSTEM OF AN SELECTED PLANT AT ARBITRARY INITIAL CONDITIONS Vladimir R. Zarić, Zoran M. Bučevac, Radiša Ž. Jovanović	7
CONDITIONAL OPTIMIZATION OF TRANSIENT BEHAVIOUR OF PLANT CONTROLLED WITH PI CONTROLLER CONSIDERING INITIAL CONDITIONS Goran Petrović, Zoran Ribar , Radiša Jovanović	13
IDENTIFICATION OF MIMO HAMMERSTEIN MODELS IN THE PRESENCE OF PIECEWISE POLYNOMIAL DISTURBANCES USING KACZMARZ ALGORITHM Vojislav Filipović, Vladimir Djordjević	19
PHILOSOPHICAL INTERPRETATION OF CONNECTION OF ROBUST STATISTICS AND FUZZY LOGIC: THE ROBUST FUZZY CLUSTERING Vladimir Djordjević, Vojislav Filipović	25
SELF-TUNING PID CONTROLLER BASED ON TIME RESPONSE CHARACTERISTICS Novak N. Nedić, Saša Lj. Prodanović	31
DESIGN OF FIXED ORDER H_{∞} CONTROLLERS WITH SPECIFIED SETTLING TIME USING D-DECOMPOSITION Ljubiša Dubonjić, Vojislav Filipović, Novak Nedić, Vladimir Đorđević	37
DATA CLASSIFICATION USING A SET OF NEURAL NETWORKS Srdjan Ribar	43
KINEMATIC AND DYNAMIC ANALYSIS OF THE PATH OF MOVEMENT OF THE ROBOT Ljiljana Pecić, Zvonko Petrović, Nikola Kostić	49
WATER DRAIN EMERGENCY SYSTEM Nikola Terzić, Dragan Pršić	55

SESSION D: MECHANICAL DESIGN AND MECHANICS

DAMPING AND SEISMIC ISOLATION BEARINGS GROUP, IN MODULAR DESIGN, FOR BRIDGES AND VIADUCTS. CONSTRUCTION AND WORKING PRINCIPLE Marian Dima, Catalin Francu	1
DYNAMICS OF THE ROTATING CANTILEVER BEAM Aleksandar Nikolić, Slaviša Šalinić	7
EXPERIMENTAL INVESTIGATION OF TRIBOLOGICAL BEHAVIOR OF JOURNAL BEARING COATED BY BABBITT ALLOYS TEGOTENAX V840 Amir Alsammarraie, Dragan Milčić, Milan Banić, Goran Radenković, Miodrag Milčić	13
SURFACE QUALITY OF MARAGING STEEL PARTS PRODUCED BY DMLS Nebojša Bogojević, Aleksandar Vranić, Nusret Muharemović, Nenad Drvar	21
MACHINING AND HEAT TREATMENT EFFECTS ON THE FATIGUE PROPERTIES OF MARAGING STEEL PRODUCED BY DMLS Snežana Ćirić-Kostić, Nebojša Bogojević, Aleksandar Vranić, Dario Croccolo, Massimiliano De Agostinis, Stefano Fini, Giorgio Olmi	27
A HEURISTIC APPROACH TO THE ESTIMATION OF MASS OF THE WASTE POWDER DURING SELECTIVE LASER SINTERING OF POLYAMIDE PA2200 Zlatan Šoškić, Simona Montanari, Gian Luca Monti, Michele Monti	37
PRACTICAL EXAMPLES OF REGENERATION OF THE DAMAGED HEAVY MACHINERY PARTS Svetislav Marković, Vladimir Stepanović, Lazar Jovičić, Milijan Ćirić, Ivan Stanišić, Miroslav Ćurčin, Nemanja Petrović	45
ANALYSIS OF FREE OSCILLATION OF SPATIAL FRAMES APPLYING THE METHOD OF CONSISTENT MASSES Rade Vasiljević	51
NUMERICAL ANALYSIS OF TRIBOMECHANICAL SYSTEM BRAKE DISC-PAD FOR HEAVY DUTY VEHICLES Nadica Stojanović, Jasna Glišović, Blaža Stojanović, Ivan Grujić	57

SESSION E: RAILWAY ENGINEERING

THE PURPOSE OF DIAGNOSTICS OF PANTOGRAPHS USED IN THE SERBIAN RAILWAYS Branislav Gavrilović, Zoran Bundalo	1
PROCESSES AND DEPENDENCIES RELATED TO NADAL'S FORMULA Dobrinka Atmadzhova	7
OSCILLATION OF RESERVOIR OF TANK-WAGON IN DYNAMIC LONGITUDINAL LOAD Dragan Petrović, Milan Bižić	17
RELIABILITY INDICATORS OF THE BRAKE DISTRIBUTORS KE 1 FOR ROLLING STOCK IN OPERATION Vasko Nikolov	23

THE IMPORTANCE OF THE RAILWAY INFRASTRUCTURE IN THE OPERATIONAL PROGRAM "TRANSPORT AND TRANSPORT INFRASTRUCTURE."	27
Mira Zafirova	
STUDY OF THE INTERACTION "WHEELSET-TRACK" OF THE ATTACKING WHEELSET OF TRAM BOGIE TYPE T81 IN EXPLOITATION IN SOFIA	33
Dobrinka Atmadzhova, Emil Mihaylov, Emil Iontchev	
OVERVIEW OF WHEEL-RAIL ROLLING CONTACT THEORIES	41
Milan Bižić, Dragan Petrović	
STUDY OF THE MOVEMENT OF THE ATTACKING TRAM WHEELSET ON TRACK WITH GAUGE 1009 MM	49
Emil Mihaylov, Emil Iontchev, Vladimir Zhekov, Zornitsa Evlogieva, Metodi Atanasov	
THE IMPACT OF THE CHARACTERISTICS OF TRAIN ON THE TRAIN BRAKING DISTANCE AT CRITICAL SECTIONS OF THE BELGRADE – BAR RAILWAY LINE	57
Dusan Vujović	
METHODS FOR CARRYING OUT TRACK MAINTENANCE AND OPTIMIZATION POSSIBILITIES	65
Metodi Atanasov	
MEASUREMENTS OF NOISE LEVELS OF FREIGHT TRAIN ON SERBIAN RAILWAYS	71
Jelena Tomić, Nebojša Bogojević	

SESSION F: THERMAL TECHNIQUE AND ENVIRONMENT PROTECTION

MODELING OF TECHNOLOGICAL EQUIPMENT AND TECHNOLOGICAL TRANSPORTATION FLOWS OF THE INDUSTRIES BINDER USING MATHEMATICAL METHODS	1
Cristina Sescu-Gal	
ENSURING PHONIC COMFORT IN URBAN ENVIRONMENT	9
Vasile Bacria, Nicolae Herisanu	
OPTIMIZATION OF FLOW SCHEMES IN RADIANT RECUPERATORS	15
Rade Karamarković, Vladan Karamarković, Miloš Nikolić, Nenad Stojčić, Miljan Marašević	
ACOUSTIC PROPERTIES OF RECYCLED RUBBER AT NORMAL INCIDENCE	23
Milan Kolarević, Branko Radičević, Nicolae Herisanu, Miloje Rajović, Vladan Grković	
DESIGNING RECUPERATOR ON A ROTARY KILN SUPPLIED WITH ENRICHED AIR DURING THE CALCINATION OF DOLOMITE	29
Miljan Marasevic, Vladan Karamarković, Nenad Stojic, Milos Nikolic, Djordje Novčić	
ANALYSIS OF DYNAMIC PINCH	37
Aleksandar Vičovac, Rade Karamarković, Dragan Pršić	
SELECTION OF THE OPTIMAL ROUTE OF TRANSPORTATION – A CASE STUDY OF TRANSPORT OF MUNICIPAL WASTE IN THE MUNICIPALITY OF TRSTENIK	45
Nikola Kostic, Milomir Mijatovic, Sasa Babic, Branimir Milosavljevic, Zvonko Petrovic	

DESIGN IMPROVEMENT OF A SIDE WATER INTAKE ON A SMALL HYDROPOWER PLANT	51
Miloš Nikolić, Vladan Karamarković, Rade Karamarković, Miljan Marašević	
MEASUREMENT AND ANALYSIS OF CHANGES IN TOTAL QUANTITY OF INJECTION DEPENDING ON THE CHANGES IN VALUE OF PRESSURE IN COMMON RAIL SYSTEM	57
Nikola Kostic, Božidar Krstic, Milomir Mijatovic, Sasa Babic, Branimir Milosavljevic	
DETERMINATION OF TRANSFER FUNCTION OF PHOTOACOUSTIC SYSTEM BY ACQUISITION CARDS WITH UNSYNCHRONIZED SIGNAL INPUT AND OUTPUT	69
Slobodan Todosijević, Nenad Drvar, Zlatan Šoškić	
PROTOTYPE SYSTEM FOR GAS TANKS CLEANING	74
Zoran Petrović, Miroljub Babić, Uglješa Bugarić, Dušan Petrović	
 SESSION G: CIVIL ENGINEERING AND MATERIALS	
MACHINE FOR IMPACT TESTING OF PLASTIC PIPES - IMPACT 2000 DESIGN, DEVELOPMENT AND PROTOTYPING	1
Ivan Milićević, Miloš Božić, Vojislav Vujičić, Radomir Slavković	
MULTI-CRITERIA SELECTION OF OPTIMAL MECHANIZATION FOR ROAD CONSTRUCTION	7
Vladimir Mandić, Saša Marinković, Jovana Bojković	
PREDICTION OF ACOUSTICAL PROPERTIES OF POROUS BUILDING MATERIALS	13
Jovana Bojković, Branko radičević, Nedeljko Manojlović, Mišo Bjelić, Vladimir Mandić, Saša Marinković,	
FLOTATION TAILINGS FROM COPPER MINING AND SMELTING PLANT AS MINERAL ADDITIVES FOR SCC	19
Saša Marinković, Vladimir Mandić, Jovana Bojković, Stefan Mihajlović	
RESEARCH OF SHEAR STRENGTH AND COMPATIBILITY BY HEAT CONDITIONING OF SHEETS FOR WATERPROOFING USED IN CONCRETE BRIDGE DECKS	27
Nikolina Porozhanova	
WELDING OF THE RESERVOIRS FOR OIL DERIVATIVES STORAGE WITH SELF-SHIELDED CORED WIRE	33
Radomir Jovičić, Olivera Erić Cekić, Aleksandar Sedmak, Sanja Petronić, Vukić Lazić	
DETAILED GEOTECHNICAL INVESTIGATIONS OF THE LANDSLIDE BOCKE	41
Mitar Đogo, Milinko Vasić	

PLENNARY SESSION

An Experimental Study on the Fatigue Response of 15-5 PH Stainless Steel Built by DMLS

D. Croccolo¹, M. De Agostinis¹, S. Fini¹, G. Olmi^{1*}, A. Vranic², S. Ciric-Kostic²

¹Department of Industrial Engineering (DIN), University of Bologna, Bologna, Italy

²Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, Serbia

The present study is focused on the fatigue strength of 15-5 PH stainless steel parts built by DMLS. Four sets of specimens were manufactured, mechanically and thermally treated, and tested under rotating bending fatigue. The samples of the first two sets were built with their longitudinal axis perpendicular or parallel to the vertical stacking direction. In both cases, a 1mm allowance was uniformly distributed. The samples of the third and the fourth sets were similarly generated, with the same orientations. The samples of the last two sets were built with cylindrical shape and with 3mm allowance at gage. The results, processed also by analysis of variance tools, indicate that, considering the first two sets, the fatigue limit, approximately 39% of the ultimate strength, is almost independent of the build orientation. Conversely, the samples with incremented allowance, which required significant machining at gage, exhibit a much higher fatigue limit, very close to the commonly accepted reference value of one-half of the ultimate strength. This is quite an interesting result, as machining seems to be able to remove the process-induced irregularities, thus making it possible to achieve comparable properties to those of wrought material.

Keywords: Fatigue strength, Stainless steel, Additive manufacturing, Direct Metal Laser Sintering, Build orientation, Machining

1. INTRODUCTION

Nowadays, there is an increasing interest towards Additive Manufacturing (AM) techniques, as this technological process is potentially capable of producing even complexly shaped parts in a relatively short time [1]. In addition, the parts can be easily built, starting from a CAD model, which is automatically processed to determine the main manufacturing parameters and the required amount of material. The parts are built layer by layer in a similar manner to rapid prototyping of plastic materials: a high-power laser beam scans over a metallic powder bed and selectively melts the powder. The melted powder solidifies and forms a layer: upon the completion of each layer, powder is added, laser scanning is repeated and a subsequent layer is deposited [2-4]. The unused powder may be partly recycled for a further process. A possible drawback of AM techniques consists in the residual stresses that may be generated during part building. Therefore, suitably shaped supports are usually applied to safely attach the built part to a rigid base-plate, thus preventing its movements through the powder bed or distortions induced by the residual stress field [2]. Direct Metal Laser Sintering (DMLS) by EOS and Selective Laser Melting (SLM) by MTT Technologies Group can be mentioned among the most important AM processes for metals [4].

The aforementioned base-plate is usually placed on a horizontal plane, and the parts are generated along a vertical stacking direction. A number of studies, involving different materials and AM processes have been focused on the possible effect of the build direction on the mechanical static and fatigue responses of the manufactured parts. Some researchers investigated a possible influence of the angle between the main axis of inertia (namely, the longitudinal axis of the specimen) and the stacking direction on the part strength. Intensive

studies were performed on selective laser melted Ti6-Al-4V samples. The results indicated that the build orientation may significantly affect the fatigue response, in particular the endurance strength in the finite life domain. A higher life for the same load entity was retrieved for the build orientation where the layer plane is parallel to the loading axis [5]. A similar effect was also observed on fracture toughness [6]. The possible effect of the build direction on the fatigue response, considering both the fatigue limit and the fatigue strength in the finite life domain was also the topic of a previous study by the same authors. This research involved MS1 Maraging steel parts, built, considering three different orientations, with post-manufacture mechanical and heat treatments. An extended experimental campaign led to the result that the fatigue response is not significantly affected by the build direction, since, for Maraging steels, post-manufacture treatments have a great role at removing sources of anisotropy [7].

Further research in the literature was focused on the mechanical behaviour 15-5 PH stainless steel parts. This type of steel is commonly used in applications such as aircraft components, or for parts under high pressure or working in harsh corrosive environments, including valves, shafts, fasteners, fittings and gears [2, 8]. A lack of studies on the effect of the build direction on the fatigue properties of this steel can be pointed out. In particular, the research in [2] was focused on the build orientation effect on the static response only. Experimental results indicated that the response is enhanced, when the load direction acts along the layer plane, but the fatigue properties for different build directions were not investigated. Other studies are documented in [9-10], but are more oriented to the effects on technological issues like machinability, rather than to the outcomes on the fatigue strength.

*Corresponding author: Giorgio Olmi, Department of Industrial Engineering (DIN), University of Bologna, Viale del Risorgimento 2, 40136 Bologna, Italy, e-mail: giorgio.olmi@unibo.it

The subject of this paper consists in an experimental study on the fatigue response of 15-5 PH stainless steel parts fabricated by the *DMLS* process. Two factors were considered: the build direction and the fabrication procedure. In particular, two different build orientations were considered, with the main axis of inertia of the parts being aligned to the load direction or perpendicular to it. Regarding the fabrication procedure, the effect of allowance and subsequent machining was studied: in one case, a conventional 1mm allowance was considered, whereas, in the second one, a larger allowance was adopted with the consequent need of machining to the core of the part. Issues of novelty arise from the lack of studies dealing with fatigue on this steel. Furthermore, the general absence of investigations on the effect of allowance on the properties of *AM* processed parts of any material must be emphasized.

2. MATERIALS AND METHODS

The experimental campaign was performed under rotating bending, following the ISO1143 [11] Standard. Specimens were designed accordingly with reference to the cylindrical smooth geometry (with uniform cross section at gauge). The smallest dimension suggested by the standard, 6mm diameter at gauge was chosen as a good compromise between standard requirements and the need of reducing production costs. A drawing of the specimen is shown in Fig. 1, with indication of all its dimensions and tolerances. The chemical composition of 15-5 PH stainless steel (by EOS GmbH – Electro Optical Systems, Krailling/Munich, Germany) is provided in Table 1 [12].

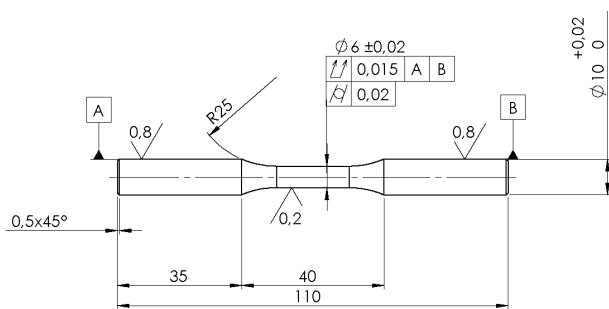


Figure 1: Specimen with 6 mm diameter at gauge in agreement with ISO 1143 Standard [11]

Table 1: Chemical composition of 15-5 PH Stainless Steel by EOS

Cr [%]	Ni [%]	Cu [%]	Mn [%]	Si [%]	Mo [%]	Nb [%]	C [%]	Fe [%]
14-15.5	3.5-5.5	2.5-4.5	≤ 1	≤ 1	≤ 0.5	0.15-0.45	≤ 0.07	Balance

The specimens were manufactured by EOSINT M280 system (EOS GmbH - Electro Optical Systems, Krailling/Munich, Germany), equipped with Ytterbium fibre laser with 200W power and emitting 0.2032mm thickness and 1064nm wavelength infrared light beam. The process takes place in an inert environment and the scanning speed may range up to 7000 mm/s. The layer thickness was set to 20 μm. A parallel scan strategy with alternating scan direction was adopted: for the subsequent layers the scanning direction was rotated to 70°, in order to prevent or reduce in-plane property variations. Some examples of the scanning patterns are shown in Fig. 2,

where arrows indicate the different scan directions at different stages of production and on different layers. A contour line was finally scanned, in order to complete the part shaping and to make its external surface as smoother as possible [13]. The machine features a working space with 250 × 250mm dimensions on the horizontal plane and a maximum height of 325mm.

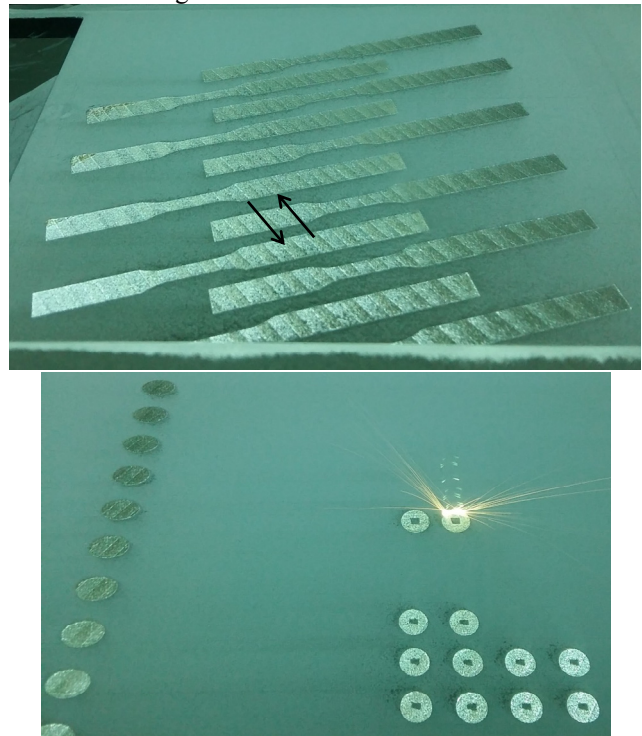


Figure 2: Some examples of the scanning patterns as the specimens are being built (arrows indicate the scan directions)

All the specimens underwent surface cleaning by micro-shot-peening: this treatment is usually performed in order to close the pores that may be induced by laser sintering. Afterwards, H900 heat treatment was performed [2, 12]: it consists in gradual heating in oven from room temperature to 482°C in 1 hour time, afterwards this temperature is kept constant for 2 hours. The parts are finally taken out of the oven and cooled in fresh air. This treatment, which is particularly effective at reducing the residual stresses, thus enhancing the fatigue response of the built parts, was performed maintaining the samples attached to their supports to prevent them from bending. Finally, the specimens underwent machining and refining by grinding with the aim of achieving the surface roughness requested by the ISO 1143 Standard [11] and of improving the fatigue performance.

Four specimen sets were manufactured: those of types #1 and #3 were built while lying horizontally on the base plate, therefore the angle between their longitudinal axis and the vertical stacking direction was 90°. Whereas, those of types #2 and #4 were built along the vertical direction: in this condition, the angle between their main axis of inertia and the stacking direction was 0°. The difference between the samples of sets #1 and #3 is that the first ones were produced with the same shape as shown in Fig. 1 with a 1mm allowance both at the gauge (diameter increased from 6 to 8 mm) and at the heads (diameter increased from 10 to 12 mm). The samples were then machined to meet the drawing specifications, regarding

dimensional and geometrical tolerances and roughness. Conversely, the samples of set #3 were built with a cylindrical shape with 12 mm diameter over their entire length. It means that the allowance was 1mm at the heads and 3mm at the specimen gage. These samples were also reworked to meet the same specifications of the drawing in Fig. 1. The same difference applies also to sets #2 (built with uniform allowance and reduced section at gage) and #4 (built with cylindrical layout). Each set was composed by 7 to 10 samples, considering that some samples were unfortunately damaged during manufacturing. Some stages of production, with reference to the aforementioned sample sets, are shown in Fig. 3.

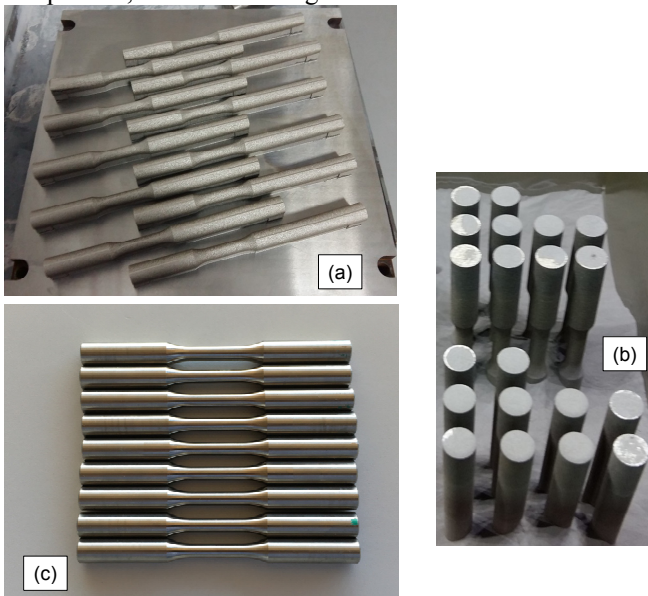


Figure 3: Some stages of sample production: (a) Set #1 samples just after DMLS manufacturing and before the heat treatment, (b) Sets #2 and #4 samples during residual powder removal with internal gage (top) and cylindrical shape (bottom), (c) Set #3 samples after machining and finishing, just before the beginning of the fatigue campaign

The fatigue campaign made it possible to obtain the *S-N* curves and the fatigue limits (*FLs*). A staircase method was applied to determine the *FL*: for this purpose, the series of failure and not-failure events was processed by the Dixon method [14-17]. A life duration of 107 cycles was set as run-out, based on the few available data on the fatigue response of sintered 15-5 PH stainless steel [2]. The Dixon method is an abbreviated staircase method that makes it possible to estimate *FL* even from a short series of nominal trials at staircase (four to six in this work). The estimation of the standard deviation makes also possible to provide an estimation of the uncertainty of the *FL* and to determine a confidence band to be applied to it. The data in the finite life domain were processed according to the Standard ISO 12107 [18]: the stress and life were linearly interpolated in logarithmic coordinates. The lower and upper limits of the *S-N* curve were been determined, based on the standard deviation of the logarithm of the fatigue life, and considering, respectively, probabilities of failure of 10% and 90% and a 90% confidence level.

3. EXPERIMENTAL PROCEDURE

All the samples were initially measured, in order to check the accomplishment of drawing requirements from the points of view of dimensions and roughness. For this purpose, a micrometre screw gauge, a digital calliper (both with the resolution of 0.01mm) and a portable surface roughness tester (with the resolution of 0.01 μm , Handysurf E-30A; Carl Zeiss AG, Oberkochen, Germany) were used. The heads at both ends and the sample gauges were measured at 90° angled points with 4 replications. Similar measurements were performed at specimen gages with 6 replications. The averaged values are collected in Tables 2-5, referred to the left-side head of the four sample sets. Regarding roughness, it has also been measured, considering 90° angled points around full diameters at both specimen heads with 8 replications. Similar measurements were then carried out at the gages after sample breakage. The averaged values are included as well in the same Tables. All the yields are generally well consistent with the requirements in ISO 1143 [11] and with drawing specifications. The samples were also checked for hardness: *HRC* Rockwell hardness was determined on all the samples with three replications. The average values, ranging from 42 to 43.5 *HRC* confirm an Ultimate Tensile Strength (*UTS*) from 1325 to 1375 MPa, which is in the order of that indicated in [12, 19-20] of 1310 MPa.

Table 2: Measurement outcomes for the sample type #1

Specimen ID	Gauge diameter			Head diameter		
	Mean [mm]	St dev. [mm]	Roughness [μm]	Mean [mm]	St dev. [mm]	Roughness [μm]
1.1	6.01	0.064	0.190	10.04	0.014	0.44
1.2	5.89	0.106	0.200	9.93	0.055	0.52
1.3	6.09	0.064	0.296	10.06	0.005	0.27
1.4	6.06	0.022	X	10.06	0.010	0.39
1.5	6.05	0.029	0.289	10.03	0.012	0.59
1.6	6.07	0.031	0.128	10.04	0.021	0.60
1.7	6.00	0.039	0.178	9.99	0.020	0.17

Table 3: Measurement outcomes for the sample type #2

Specimen ID	Gauge diameter			Head diameter		
	Mean [mm]	St dev. [mm]	Roughness [μm]	Mean [mm]	St dev. [mm]	Roughness [μm]
2.1	6.03	0.035	0.400	10.01	0.005	0.38
2.2	6.01	0.029	0.323	10.01	0.002	0.30
2.3	6.02	0.036	0.413	10.01	0.004	0.31
2.4	5.98	0.044	0.246	10.01	0.005	0.41
2.5	6.02	0.027	0.425	10.01	0.003	0.35
2.6	6.00	0.026	0.338	10.00	0.002	0.35
2.7	6.01	0.035	X	10.01	0.002	0.37
2.8	6.02	0.036	0.340	10.00	0.003	0.35
2.9	6.01	0.025	0.370	10.00	0.003	0.36
2.10	6.00	0.038	0.308	10.00	0.010	0.44

Table 4: Measurement outcomes for the sample type #3

Specimen ID	Gauge diameter			Head diameter		
	Mean [mm]	St dev. [mm]	Roughness [μm]	Mean [mm]	St dev. [mm]	Roughness [μm]
3.1	6.01	0.014	0.270	10.02	0.002	0.64
3.2	6.01	0.016	0.340	10.02	0.005	0.48
3.3	6.01	0.011	X	10.01	0.003	0.71
3.4	6.00	0.009	0.260	10.02	0.009	0.65
3.5	6.01	0.010	X	10.02	0.003	0.50
3.6	6.00	0.014	0.440	10.02	0.005	0.59
3.7	6.01	0.008	0.250	10.02	0.003	0.63
3.8	6.01	0.009	0.400	10.02	0.003	0.64
3.9	6.00	0.012	0.350	10.02	0.004	0.63

Table 5: Measurement outcomes for the sample type #4

Specimen ID	Gauge diameter			Head diameter		
	Mean [mm]	St dev. [mm]	Roughness [μm]	Mean [mm]	St dev. [mm]	Roughness [μm]
4.1	6.03	0.041	0.300	10.00	0.002	0.22
4.2	6.00	0.019	0.369	10.00	0.003	0.28
4.3	6.00	0.028	X	10.00	0.003	0.23
4.4	6.01	0.040	0.363	10.00	0.003	0.30
4.5	6.00	0.036	X	10.00	0.002	0.32
4.6	6.01	0.040	0.398	10.00	0.003	0.31
4.7	6.01	0.026	X	10.00	0.003	0.25
4.8	6.02	0.032	0.328	10.00	0.003	0.27
4.9	6.00	0.019	0.478	10.00	0.003	0.24
4.10	6.00	0.018	0.280	10.00	0.002	0.23

The specimens were tested under rotating bending fatigue by a rotary bending testing machine, where the specimen is loaded in the four-point bending configuration, so that bending moment keeps constant over the entire sample length, and in particular at its gage [14]. The sample was pinched at its ends by a pressure of approximately 70 MPa [21-22]. All the tests were conducted under fully reversed bending load (stress ratio $R = -1$) at the frequency f of 60 Hz. At the end of the experimental campaigns, some samples were cut and resin embedded. In particular, transverse sections of the gages and longitudinal sections of the heads were considered. Micrographic analyses were performed both at the gages and at the ends, following chemical attacks according to this recipe. 20 cc of Glycerol ($\text{C}_3\text{H}_8\text{O}_3$) and 10 cc Nitric Acid (HNO_3) were mixed together and the same was done with 20 cc of Chloridric Acid (HCl) and 10 cc of Hydrogen peroxide (H_2O_2). These two mixtures were finally 50%-50% mixed together.

4. RESULTS

The results of the fatigue tests for type #1 specimens (horizontally built, with 1mm allowance) are collected in Table 6: in particular, sample identifier, the load level in terms of the applied force and of the nominal stress at gage, the observed life and the test outcome are reported.

Table 6: Data retrieved from the tests on the sample type #1

Specimen ID	Load [N]	Stress [MPa]	Life [N]	Failure
1.1	127.2	420	---	N
1.2	166.6	550	144,726	Y
1.3	158.8	524	167,829	Y
1.4	151.5	500	---	N
1.5	151.5	500	728,708	Y
1.6	143.9	475	8,423,284	Y
1.7	197.2	651	47,315	Y

Table 7: Data retrieved from the tests on the sample type #2

Specimen ID	Load [N]	Stress [MPa]	Life [N]	Failure
2.1	197.2	651	4,834,809	Y
2.2	215.4	711	1,871,476	Y
2.3	178.7	590	108,926	Y
2.4	178.7	590	68,686	Y
2.5	142.8	470	---	N
2.6	169.6	560	43,729	Y
2.7	160.6	530	---	N
2.8	169.6	560	2,807,208	Y
2.9	160.6	530	2,564,861	Y
2.10	151.5	500	5,047,111	Y

Table 8: Data retrieved from the tests on the sample type #3

Specimen ID	Load [N]	Stress [MPa]	Life [N]	Failure
3.1	206.0	680	---	N
3.2	215.4	711	3,274,162	Y
3.3	206.0	680	---	N
3.4	215.4	711	8,364,965	Y
3.5	206.0	680	---	N
3.6	242.4	800	183,582	Y
3.7	233.3	770	368,551	Y
3.8	224.2	740	297,241	Y
3.9	224.2	740	2,850,771	Y

Table 9: Data retrieved from the tests on the sample type #4

Specimen ID	Load [N]	Stress [MPa]	Life [N]	Failure
4.1	196.9	650	6,082,766	Y
4.2	215.4	711	7,366,205	Y
4.3	242.4	800	532,725	Y (NOT VALID)
4.4	178.7	590	---	N
4.5	187.8	620	1,256,019	Y (NOT VALID)
4.6	187.8	620	8,932,232	Y
4.7	178.7	590	---	N
4.8	187.8	620	6,397,216	Y
4.9	242.4	800	260,944	Y
4.10	233.3	770	503,334	Y

The results of sets #2 (vertically built, with uniform allowance), #3 (horizontally built, with greater allowance at gage) and #4 (vertically built, with greater allowance at gage) are respectively reported in Tables 7-9, where the same data are present. A not failure outcome indicates that the trial was stopped upon run-out without breakage occurrence. In the case of failure, it was of course checked that specimen separation had occurred at gage. Afterwards, the fracture surfaces were observed to make sure that a fatigue initiation and propagation mechanism was actually responsible of the observed failure. Most failures regularly occurred at gage, but in two cases, for the same sample set (Set #4), unusual and unexpected failures at specimen heads were observed. One of these failures is depicted in Fig. 4. It must be remarked that this outcome is not completely new, as it had also been observed (again in two cases) in the previous research regarding Maraging steels. In that study, an analysis by dye penetrants had indicated the presence of some spots of unconformable roughness, which were likely to have triggered the crack in combination with the clamping

pressure. In the present study, the roughness at sample ends was carefully checked by multiple measurements and was found to be consistent with specifications. The analysis was therefore deepened by micrographic analyses, as described in the previous Section.



Figure 4: Unexpected failure at sample head

The samples that were involved in the aforementioned outcome were of course discarded for further processing regarding the fatigue response. The final outcomes of these two trials are therefore tagged as NOT VALID in Table 9. The other results were anyway sufficient to determine both the sloping part of the S-N curve and the fatigue limit.

5. DISCUSSION

The results reported in the previous Section were initially processed, in order to determine the fatigue curves in the finite life domain. The S-N curves, retrieved as linear regressions in double logarithmic scale, are plotted in the graphs in Figs 6-9 for sets #1 to #4 respectively. The corresponding equations that yield the expected life as a function of the actual stress level are included in the figures. The related maximum likelihood bands at the 90% confidence level and the experimental data are also plotted in the same diagrams, following the recommendations of [18]. The experimental results can be generally well fitted along a straight line with a linear correlation coefficient (R^2) up to 0.8.

The slopes of the interpolating lines were also determined during the regression procedure. The angle between the S-N line and the vertical axis is 86° for set #1, 88° for set #2, 88° for set #3 and 85° for set #4. The resulting inclination can be compared to those of the S-N curves determined for Maraging Steel MS1: considering Ref. [7] the angles of the determined curves were ranging between 75° and 80° . The generally higher angle retrieved for stainless steel indicates that its S-N curves have a less steep trend, where small variations of the state of load may correspond to huge variations of the fatigue life, from the order of 10^5 to almost 10^7 cycles. A great role seems to be due to the level of roughness: as documented by the data in Tables 2-5, related values were quite low in this study, ranging from 0.2 to $0.3\mu\text{m}$ as an average. The experimentations reported in [19-20] were performed on samples of the same material and with comparable roughness and led to a nearly horizontal curve, with a similar slope. Conversely, the experimentations in [2], involving the same stainless steel produced by SLM, were performed on samples with a 10-time higher roughness and led to a much lower fatigue resistance with a particularly sharp drop of the curve for increasing life (corresponding to a much lower angle).

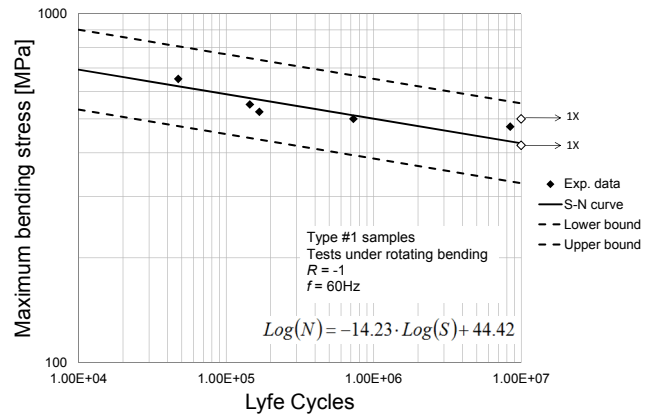


Figure 5: S-N curve for type #1 specimens (arrows indicate run-outs)

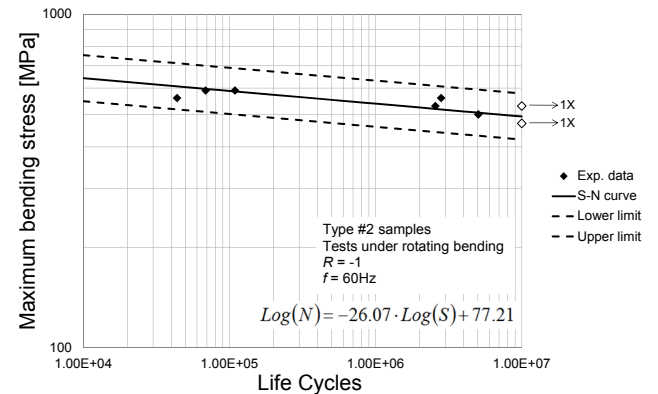


Figure 6: S-N curve for type #2 specimens (arrows indicate run-outs)

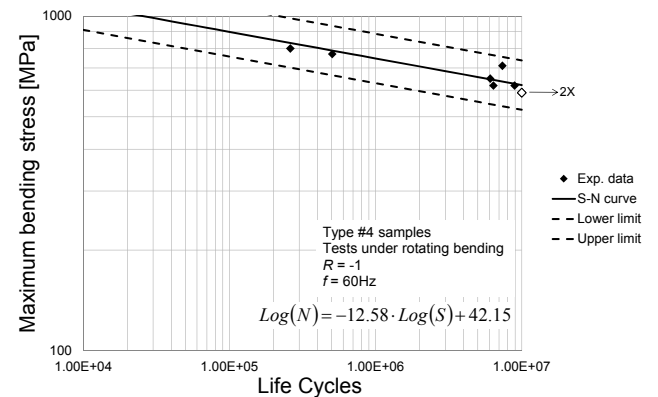


Figure 7: S-N curve for type #3 specimens (arrows indicate run-outs)

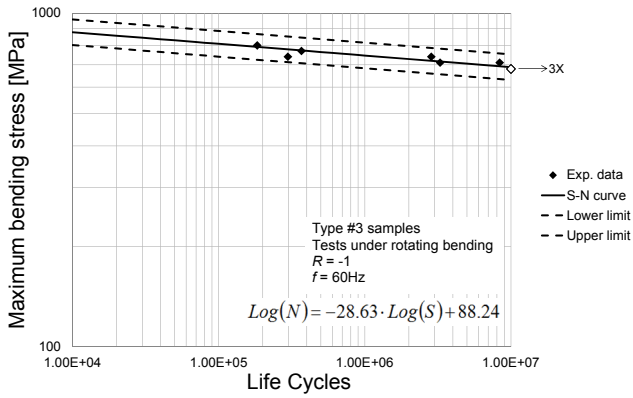


Figure 8: S-N curve for type #4 specimens (arrows indicate run-outs)

The results of the trials at staircase were processed by the Dixon method and led to the estimation of the *FLs* collected in the bar graph in Fig. 10, along with related confidence bands. The limit for the sample type #1 was estimated as 480 MPa, a well comparable value to that for type #2, 507 MPa. The other limits were conversely significantly higher: 701MPa for type #3 and 605MPa for the fourth sample set.

It is interesting to compare the determined *FLs* to the *UTS* strength of the material according to [12, 19-20], considering that a commonly accepted ratio (*FL/UTS*) is approximately 50% for metallic materials [23]. The *FLs* for horizontally and vertically built samples with 1mm allowance are quite close each other and correspond to 37% and 39% of the *UTS*. This isotropic behavior is consistent to that reported in [7] for Maraging steels. Moreover, the determined ratios to *UTS* are lower than 50%, but about ten points higher than the same ratio determined for Maraging steel. It indicates that, on one hand the *DMLS* processed parts have a lower fatigue limit than expected, but that this detrimental effect is less significant for 15-5 Stainless steel rather than for Maraging steel.

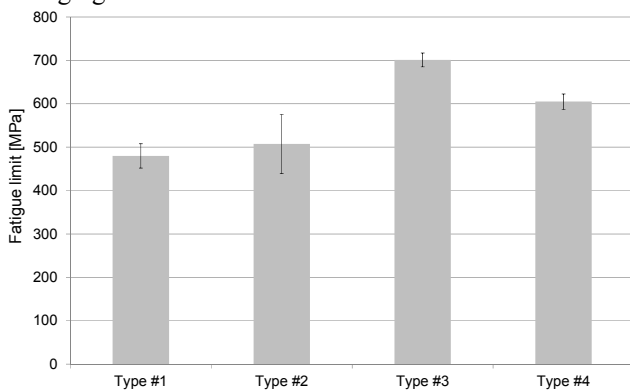


Figure 9: Bar graph summarizing the fatigue limits for the four sample types along with their confidence bands

Regarding the *FLs* for sets #3 and #4, ratios to *UTS* are respectively 54% and 46%. This outcome indicates that a post-manufacture machining up to the material core seems to have a beneficial effect on the fatigue response. In particular, the post-manufacture machining seems to be able to remove the irregularities at the surface layers, where, as remarked in the Materials and Methods Section, contour lines are scanned to complete the part shaping.

These irregularities may be able to trigger fatigue cracks and may therefore be responsible of the aforementioned lower fatigue response of *DMLS* (and generally *AM*) processed parts. As a consequence, the ratio to *UTS* is significantly increased up to the reference value of 50%. Moreover, the response is better, when the load direction acts on the layer plane, which is consistent to the results in [5-6] for Maraging steels and in [2] for the same steel under static load.

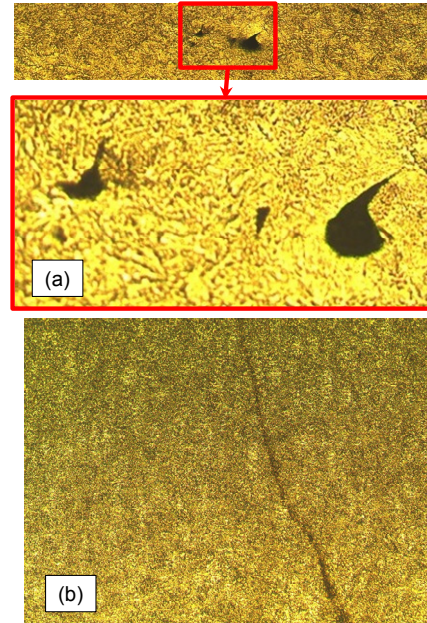


Figure 10: (a) Example of a void; (b) transverse crack detected at specimen head

Finally, some micrographic and fractographic analyses were performed on the samples, to check the material structure and to investigate the possible reasons for the unexpected failures at heads. It can be remarked that some voids were observed: an example is shown in Fig. 10 (a). These voids are likely to have triggered most of these irregular failures, acting in combination with the clamping pressure. In addition, it is interesting to observe that a transverse crack was observed at the head of a specimen of Set #4 that had regularly broken down at the gage. It may indicate that another crack was propagating at the head, but that separation at the gage occurred earlier.

The visual observation of the regular cracks at gage by stereo and optical microscopes indicated that pores with 30-40µm diameter just beneath the surface (at about 80µm depth) were responsible for the initiation of most cracks. An example is shown in Fig. 11.

Finally, some micrographies were devoted to the observation of the microstructure generated by the building process: the picture in Fig. 12 (a) was taken along the build plane: it can be observed that laser scans on contiguous planes are well visible and the related angle (highlighted) is consistent with the process setting. A micrography along a perpendicular plane (parallel to the vertical stacking direction) is finally depicted in Fig. 12 (b), where the build direction is also indicated. These outcomes indicate that the *AM* induced structure is still well visible, even after the recommended heat treatments.

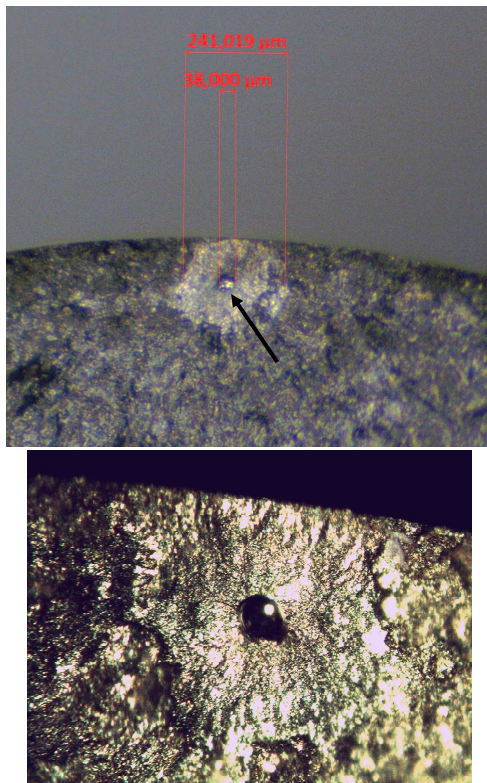


Figure 11: Example of a pore that triggered a crack

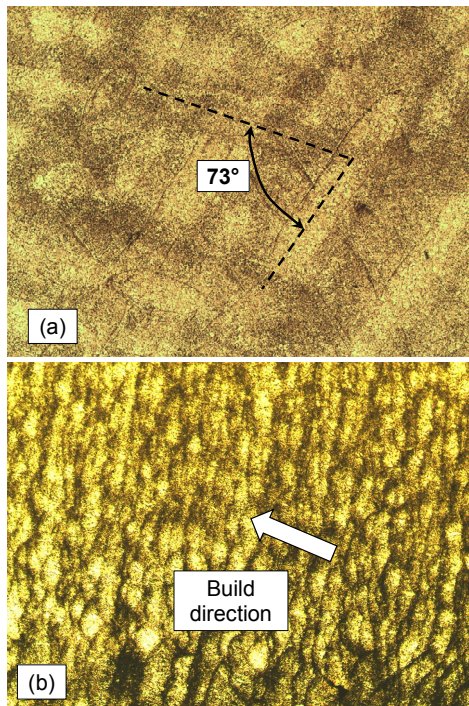


Figure 12: Micrographic analyses on unmachined horizontally built samples: (a) laser scans on the build plane (contiguous planes are visible, relative angle highlighted), (b) layers along the stacking direction

6. CONCLUSIONS

This study aims at defining the fatigue strength of 15-5 PH Stainless Steel manufactured by direct selective laser sintering (DMLS) machine. Literature survey indicated that Additive Manufacturing (AM) techniques, such as DMLS or Selective Laser Melting are highly effective at producing even complicated parts. Moreover, there is a lack of data concerning the fatigue response of

AM processed parts of the aforementioned stainless steel. Four sample sets were manufactured: horizontally and vertically built with uniform allowance and with an incremented allowance at specimen gage (manufactured as cylindrical parts). This experiment can therefore be regarded as a two-factor plan with two levels (2²). The results indicate that the fatigue curves have a high inclination with respect to the vertical axis and that the fatigue limits of horizontally and vertically built samples with uniform allowance are almost the same. The ratio of the fatigue limits to the ultimate tensile strength is approximately 38%. Conversely, when considering samples with higher allowance, which required the removal of a remarkable amount of material at gage, the fatigue limit is averagely one-half of the ultimate strength. Machining up to the material core seems to be able remove the additive process induced irregularities at the external layers that reduce the fatigue strength of AM processed parts. Moreover, the limit was higher for samples where the layer planes are parallel to the load direction. Afterwards, fractographic and micrographic analyses made it possible to provide explanations to the observed outcomes, and to check the microstructure resulting from the additive process.

ACKNOWLEDGEMENTS

The research presented in this paper has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 734455.

REFERENCES

- [1] F. Abe, K. Osakada, M. Shiomi, K. Uematsu and M. Matsumoto, "The manufacturing of hard tools from metallic powders by selective laser melting", *Journal of Materials Processing Technology*, Vol. 111, pp. 210-213, (2001)
- [2] H.K. Rafi, T.L. Starr and B.E. Stucker, "A comparison of the tensile, fatigue, and fracture behaviour of Ti-6Al-4V and 15-5 PH stainless steel parts made by selective laser melting", *The International Journal of Advanced Manufacturing Technology*, Vol. 69, pp. 1299-1309 (2013)
- [3] E. Santos, S. Masanari, K. Osakada and T. Laoui, "Rapid manufacturing of metal components by laser forming", *International Journal of Machine Tools and Manufacture*, Vol. 46, pp. 1459-1468 (2006)
- [4] E. Herderick, "Additive Manufacturing of Metals: A Review", *Proceedings of "Materials Science and Technology (MS&T)"*, October 16-20, 2011, Columbus, Ohio, (2011)
- [5] P. Edwards and M. Ramulu, "Fatigue performance evaluation of selective laser melted Ti-6Al-4V", *Materials Science and Engineering A*, Vol. 598, pp. 327-337, (2014)
- [6] P. Edwards and M. Ramulu, "Effect of build direction on the fracture toughness and fatigue crack growth in selective laser melted Ti-6Al-4V", *Fatigue & Fracture of Engineering Materials & Structures*, Vol. 38, pp. 1228-1236 (2015)
- [7] D. Croccolo, M. De Agostinis, S. Fini, G. Olmi, A. Vranic and S. Ciric-Kostic, "Influence of the build

orientation on the fatigue strength of EOS maraging steel produced by additive metal machine", *Fatigue & Fracture of Engineering Materials & Structures*, Vol. 39, pp. 637-647, (2016)

[8] M. Abdelshehid, K. Mahmodieh, K. Mori, L. Chen, P. Stoyanov, D. Davlantes, J. Foyos, J. Ogren, R. Clark Jr. and O.S. Es-Said, "On the correlation between fracture toughness and precipitation hardening heat treatments in 15-5PH Stainless Steel", *Engineering Failure Analysis*, Vol. 14, pp. 626-631, (2007)

[9] K. Ozbaysal and O.T. Inal, "Age-hardening kinetics and microstructure of PH 15-5 stainless steel after laser melting and solution treating", *Journal of Materials Science*, Vol. 29, pp. 1471-1480, (1994)

[10] D. Palanisamy, P. Senthil and V. Senthilkumar, "The effect of aging on machinability of 15Cr-5Ni precipitation hardened stainless steel", *Archives of Civil and Mechanical Engineering*, Vol. 16, pp. 53-63, (2016)

[11] International Organization for Standardization ISO 1143:2010, "Standard - Metallic materials – Rotating bar bending fatigue testing", International Organization for Standardization (ISO), Geneva, Switzerland, (2010)

[12] <http://www.eos.info/material-m>

[13] D. Croccolo, M. De Agostinis and G. Olmi, "Experimental characterization and analytical modelling of the mechanical behaviour of fused deposition processed parts made of ABS-M30", *Computational Materials Science*, Vol. 79, pp. 506-518, (2013)

[14] G. Olmi and A. Freddi, "A new method for modelling the support effect under rotating bending fatigue: Application to Ti-6Al-4V alloy, with and without shot peening", *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 36 (10), pp. 981-993, (2013)

[15] W.J. Dixon and F. Massey Jr., "Introduction to Statistical Analysis", McGraw-Hill, New York, United States, (1983)

[16] G. Olmi, M. Comandini and A. Freddi, "Fatigue on shot-peened gears: Experimentation, simulation and sensitivity analyses", *Strain*, Vol. 46 (4), pp. 382-395 (2010).

[17] B. Van Hooreweder, D. Moens, R. Boonen and P. Sas, "The critical distance theory for fatigue analysis of notched aluminium specimens subjected to repeated bending", *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 35, pp. 878-884 (2012)

[18] International Organization for Standardization ISO 12107:2003, "Metallic Materials – Fatigue Testing – Statistical Planning and Analysis of Data", International Organization for Standardization (ISO), Geneva, Switzerland, (2003)

[19] ASM International, "ASM Handbook", Vol. 1, Materials Park, Ohio, (2016)

[20] ASM International, "ASM Handbook", Vol. 2, Materials Park, Ohio (2016)

[21] D. Croccolo, M. De Agostinis and G. Olmi, "Fatigue life characterisation of interference fitted joints", *Proceedings 2013 ASME International Mechanical Engineering Congress and Exposition*, in Proc. IMECE 2013, San Diego, CA, United States, Vol. 2B, V02BT02A015 (10 pages), (2013)

[22] D. Croccolo, M. De Agostinis, S. Fini, A. Morri and G. Olmi G, "Analysis of the Influence of Fretting on the Fatigue Life of Interference Fitted Joints", *Proceedings ASME - American Society of Mechanical Engineers*, Montreal, Canada, 14-20, November, 2014, Vol. 2B: Advanced Manufacturing, pp. 1-10, 2014.

[23] G. Niemann, H. Winter, B.R. Hohn, "Maschinenelemente", Springer-Verlag, Berlin, Germany (2005)

CIP - Katalogizacija u publikaciji -
Narodna biblioteka Srbije, Beograd

INTERNATIONAL Triennial Conference Heavy
Machinery (9 ; 2017 ; Zlatibor)
Proceedings [Elektronski izvor] / The Ninth International
Triennial Conference Heavy Machinery HM 2017,
Zlatibor, June 28 - July 1 2017 ; [editor Milomir Gašić].
- Kraljevo : Faculty of Mechanical and Civil Engineering,
2017 (Vrnjačka Banja : SaTCIP), 628 str. : ilustr; 29 cm

Sistemska zahtevi: Nisu navedeni. - Naslov sa naslovne
strane dokumenta. -Tiraž 100. -Bibliografija uz svaki rad.

ISBN 978-86-82631-89-7

621(082)(0.034.2)

621.86/.87(082)(0.034.2)

629.3/.4(082)(0.034.2)

622.6(082)(0.034.2)

681.5(082)(0.034.2)

COBISS.SR-ID 239679756