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Comparative HAZ softening analysis of three different automotive aluminium alloys by physical simulation
Komparativna analiza fizičkom simulacijom omekšavanja ZUTa tri različite aluminijumske legure za vozila

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Abstract

The development of high strength aluminium alloy has revolutionized the automotive industry with innovative manufacturing and technological process to provide high performance components, weight reduction and also diversified the application field and design consideration for the automotive parts that work under severe conditions, but the selection of proper production parameters is most challenging task to get excellent results. Growing industrial demand of aluminium alloys led to the development new welding technologies, processes and studies of various parameters effects for its intended purposes. The microstructural changes that lead to loss of hardening and thereby mechanical strength in the HAZ welded joint even though the base materials are heat treatable and precipitation hardened. So, our goal is to analyse HAZ softening and analyse the sub zones as a function of parameter. In this paper, the influence of weld heat cycle on heat affected zone (HAZ) is physically simulated for Tungsten Inert Gas Welding (TIG) using Gleeble 3500 thermomechanical simulator for three different automotive aluminium alloy (AA5754-H22, AA6082-T6 & AA7075-T6) plate of 1 mm thickness. In order to simulate the sub-zones of the heat-affected zone, samples were heated to four different HAZ peak temperatures (550 °C, 440 °C, 380 °C and 280 °C), two linear heat input (100 J/mm and 200 J/mm) by the application of Rykalin 2D model. A series of experiments were performed to understand the behaviour, which make it possible to measure the objective data on the basis of the obtained image of the aluminium alloys tested with

Rezime

Razvoj aluminijumskih legura visoke čvrstoće je uveo revoluciju u automobilsku industriju, kroz inovativne izrade i tehnološke procese, a sve u cilju obezbeđivanja komponenti visokih performansi, smanjenja težine, različitih primena i konstrukcija za automobilske delove koji funkcionišu pod teškim uslovima. Međutim izbor preciznih proizvodnih parametara predstavlja najveći izazov da bi se ostvarili najbolji rezultati. Rastući industrijski zahtevi za aluminijumskim legurama vodi ka razvoju novih tehnologija zavarivanja, zatim procesa kao i odgovarajućih studija koje izučavaju efekate uticaja različitih parametara. Mikrostrukturalne promene dovode do gubitka tvrdoće, a time i mehaničke čvrstoće u zoni uticaja toplote (ZUT) zavarenih spojeva bez obzira što je osnovni metal termički obradljiv i precipitaciono ojačan. Cilj ovog rada je da analizira omkšavanje ZUTa i subzona u zavisnosti od primenjenih parametara. Izvršeno je ispitivanje uticaja toplotnog ciklusa zavarivanja na zonu uticaja toplote (ZUT) fizičkom simulacijom za slučaj zavarivanja netopivom volframovom elektrodom u zaštitnoj atmosferi inertnog gasa (TIG), a primenom termomehaničkog simulatora Gleeble 3500. Ispitivanja su vršena na tri različite aluminijumske legure za primenu u vozilima (AA5754-H22, AA6082-T6 i AA7075-T6), u obliku ploča debljina 1mm. U cilju simulacija subzona u zoni uticaja tolote, uzorci su zagrevani do četiri različite maksimalne - vršne temperature karakteristične za ZUT (550 °C, 440 °C, 380 °C i 280 °C) i sa dva različita linearna unosa toplote (100 J/mm i 200 J/mm) koji su u skladu sa primenjenim 2D Rykalin-ovim modelom prenosa heat-affected zone tests in a Gleeble 3500 physical simulator. The main objective is to achieve the weldability of three different automotive aluminium alloys and their comparison based on the welding parameters like heat input. Further, the investigation of HAZ softening and microstructure of the specimens were tested and analysed using Vicker's hardness test and optical microscope respectively. The paper focuses on HAZ softening analysis of different grades of aluminium alloys for automotive application.

toplote. Izvršena je serija eksperimenata, da bi se razumelo ponašanje metala, na osnovu čega je moguće meriti objektivne podatke o aluminijumskim legurama koje su testirane na Gleeble 3500 fizičkom simulatoru, a pod uslovima koji postoje u ZUTu. Glavni cilj istraživanja je određivanje zavarljivosti tri različite aluminijumske legure za vozila i njihovo poređenje na osnovu parametara zavarivanja, kao što je u ovom slučaju unos toplote. Pored toga, ispitivanje omekšavanja ZUTa i promene u mikrostrukturi je ispitivano i analizirano primenom Vikers uređaja za merenje tvrdoće i optičkom mikroskopijom. Rad je fokusiran na analizu omekšavanja ZUTa za različite kvalitete aluminijumskih legura za primenu u automobilskoj industriji.

1. Introduction

Keeping in view the environmental changes that have taken place in recent years and the changing consumer requirements, there is a growing need for research into lightweight structural materials. Such changing consumer requirements include, for example, improved fuel efficiency, reduction of exhaust emissions, and increased operational efficiency in various transport applications. Also, increasingly stringent environmental regulations have fundamentally influenced the development of automotive materials and technologies [1]. One way of satisfying this endeavour is to reduce emissions of pollutants by reducing vehicle weight. Due to this, in the last few years, the use of aluminium alloys in vehicles shows an unprecedented increase compared to all other applications. Aluminium alloys have great potential for mass reduction, because of their low density, with a high strength and toughness comparable to steel by the application of alloying elements. Another remarkable feature of aluminium is that it can be recycled under excellent conditions. A wide variety of alloys are available for the production of welded structures and finished products made using aluminium and its alloys. Each of the alloys and alloy types have different properties that are important to both the designer and the manufacturer. The practical marking system used by Aluminium Association (AA), which groups the alloys according to their main alloying elements, was taken over by EN 573. The marking system denotes the alloys with a four-digit numerical sign, in the main alloy grouping [2] as shown in Fig. 1.

1. Uvod

Imajući u vidu promene životne sredine koje su se dogodile zadnjih godina i promena zahteva potrošača, raste potreba za istraživanjem u oblasti lakih konstrukcionih materijala. Takve promene zahteva potrošača uključuju na primer smanjenje potrošnje goriva, smanjenje emisije izduvnih gasova i povećanu operativnost za različite vrste transporta. Takođe sve stroţiji ekološki propisi značajno utiču na razvoj materijala i tehnologija za vozila [1]. Jedan od načina za zadovoljavanje ovih zahteva je smanjenje zagađenja kroz smanjenje težine vozila. Zbog ovih zahteva zadnjih nekoliko godina, primena aluminijumskih legura u vozilima pokazuje izuzetno visoko povećanje u poređenju sa svim ostalim primenama.
Aluminijumske legure imaju veliki potencijal za smanjenje težine, zbog svoje male gustine, visoke čvrstoće i žilavosti u pređenju sa legiranim čelicima. Druga značajna prednost aluminijuma je da može da se reciklira u visokom procentu.
Široki spektar legura zasnovanih na aluminijumu i aluminijumskim legurama se primenjuju za izradu zavarenih konstrukcija i gotovih proizvoda. Svaka od legura i tipa legura ima različite osobine, koje su značajne za projektante i prizvođače. Praktičan sistem označavanja Al legura koji koristi Aluminium Association (AA), grupiše legure prema njihovim glavnim legirajućim elementima, što je preuzeo i standard EN 573. Legure se označavaju sa četvorocifrenom numeričkom oznakom u glavne grupe legura [2], kao što je prikazano na Slici 1.

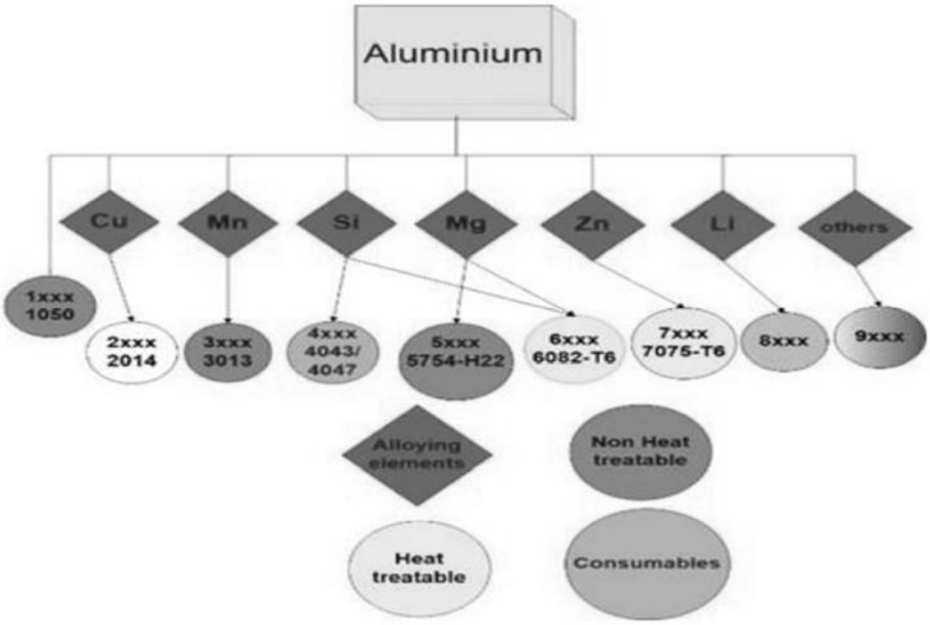

Figure 1. *Grouping of aluminium alloy [3]*
Slika 1. *Grupe alumijumskih legura [3]*

The formability of modern aluminium materials in the automotive industry is fundamentally impaired by the alloys found in them and by the brittle dispersions resulting from them [4]. The reduction in formability is such that there is already a risk of cracking during the shaping of parts with simple geometric design, as well as a high degree of shrinkage [5].

The aims of this paper to conduct a series of experiments and understand the behaviours which make it possible to measure the objective data based on the obtained results of the aluminium alloys tested with heat-affected zone tests in a physical simulator. The main objective is to achieve the weldability of three different automotive aluminium alloys and their comparison based on the welding parameters like heat input. Further, the investigation of HAZ softening and microstructure of the specimens were tested and analysed using Vicker's hardness test and optical microscope respectively. The paper focuses on HAZ softening analysis of three different automotive aluminium alloy (AA5754- H22, AA6082-T6 & AA7075-T6).

Plastičnost modernih aluminijumskih legura u automobilskoj industriji je značajno smanjena legirajućim elementima u njima i nihovim krtim uključcima [4]. Smanjenje plastičnosti je takva da postoji rizik stvaranja prslina za vreme oblikovanja u jednostavne geometrijske oblike, kao i visok stepen skupljanja [5].

Cilj ovog rada je izvođenje serije eksperimenata na fizičkom simulatoru, da bi se razjasnilo ponašanje materijala - aluminijumskih legura u zoni uticaja toplote pri zavarivanju i da se mere objektivni podaci dobijeni na osnovu ispitivanja. Glavni cilj je postizanje dobre zavarljivosti tri različite aluminijumske legure za vozila i njihovo poređenje zasnovano na parametrima zavarivanja, kao što je unos toplote. Pored toga, ispitivanje omekšavanje ZUTa i mikrostruktura uzoraka, koje je ispitivano i analizirano primenom merenja Vickers tvrdoće i primenom optičke mikroskopije. Rad se fokusirao na analizu omekšavanja ZUTa za tri različite aluminijumske legure za vozila (AA5754-H22, AA6082-T6 i AA7075-T6).

2. Aluminium alloys & weldability

Aluminium has a density of approximately one third compared to steel and is used in applications where a high strength/weight ratio is required [6]. Aluminium components can be joined by several different methods, including welding, brazing, soldering, adhesive bonding, and mechanical methods such as riveting and bolting [7]. The welding processes preferred more as compared to other process to join aluminium products, as it can

2. Aluminijumske legure i zavarljivost

Aluminijum ima gustinu koja je jedna trećina gustine čelika i primenjuje se tamo gde se zahteva visok odnos čvrstoće i težine [6]. Aluminijumske komponente se mogu spajati na nekoliko različitih načina, uključujući zavarivanje, lemljenje, tvrdo lemljenje, adhezivno spajanje i mehaničke metode, kao što su zakivanje i spajanje vijcima [7]. Proces zavarivanja je u prednosti u odnosu na druge procese spajanja kod aluminijumskih proizvoda, provide high productivity, weld quality, welding speed, manufacturing flexibility, and easy automation [8, 9]. Rather metallurgical, challenge in aluminium welding is the occurrence of hot cracks during solidification. The susceptibility to solidification cracking defines the weldability of an aluminium alloy and depends upon the alloy system, the welding conditions and the weld geometry [7, 10]. In some alloys, this effect is so severe that welding without cracking cannot be obtained [7]. Unfortunately, this concerns many high-strength Al alloys (5xxx and 6xxx alloys). For this reason, an important way to increase the weldability of crack-sensitive Al alloys is the use of a filler material with a different composition and shorter solidification interval. In this way, the weld metal chemical composition and freezing range is shifted away from the crack-sensitive range [11].

If we consider the typical strength distribution in the cross section of the fusion welded joint of different kind of aluminium alloys, we can see that a significant strength reduction happens in the weld and HAZ of heat treatable aluminium alloys. However, in case of solid-state pressure welding the softening is lower compared to fusion welding [12]. The wrought base metals used were Alloy AA 5754 (AlMg3), known for applications in the automotive industry and for hermetic housings in the electronic industry. AA 5754 is an aluminium magnesium alloy, and the most prominent feature is the high resistance to oxidation and corrosion. Thus, it has been extensively used in pressure vessels, tanks, trucks, and shipbuilding. The 6082-T6 alloy is designating as a 6xxx-series of aluminium which have Mg and Si as the main alloying elements. Due to its high resistance to stress corrosion cracking it is often used as construction material for several components in automotive industry, plant construction and shipbuilding [13]. These alloys can be anodized, which may be necessary for products where hard, high-strength, corrosion-resistant surfaces are important. In hard anodized condition, they are ideal for braking systems, electronic valves and pistons [2]. A further important influence on cracking behaviour is the chemical composition of the base metal. The alloy 6082 (AlSi1MgMn) has a higher susceptibility to solidification cracking than other Al-Mg-Si alloys, which is known from ring casting tests for a wide range of Al-Mg-Si alloys [14]. Reasons are the Mg (0.75 wt. %) and Si (0.86 wt. %) concentration of the alloy that explain the high susceptibility [9]. In addition, the composition and distribution of the interdendritic liquid influence strongly the tendency for solidification cracking,

obzirom da on obezbeđuje visoku produktivnost, kvalitetan spoj, veliku brzinu spajanja, proizvodnu fleksibilnost i laku automatizaciju procesa [8, 9]. Pri zavarivanju aluminijuma postoje metalurški izazovi, kao što je pojava toplih prslina za vreme očvršćavanja. Osetljivost na pojavu prslina usled očvršćavanja definiše zavarljivost aluminijumskih legura i zavisi od sistema legiranja, uslova zavarivanja i geometrije spoja [7, 10]. Kod nekih legura, taj efekat je toliko izražen da zavarivanje bez prisustva prslina se ne može ostvariti [7]. Nažalost ovo se javlja kod mnogih Al legura visoke čvrstoće (legure 5xxx i 6xxx). Iz tog razloga, jedan od važnih načina da se poveća zavarljivost Al legura je upotreba dodatnog materijala drugačijeg hemijskog sastava i primena kraćeg intervala očvršćavanja. Na taj način, hemijskim sastavom metala šava i intervalom očvršćavanja se vrši pomeranje iz oblasti osetljivosti na pojavu prslina [11].

Ako se posmatra karakteristična raspodela čvrstoće u poprečnom preseku zavarenog spoja različitih aluminijumskih legura, može se uočiti značajno smanjenje čvrstoće u spoju i ZUTu termički obradljivih aluminijumskih legura. Međutim u slučaju zavarivanja u čvrstom stanju pod pritiskom, omekšavanje je manje u odnosu na zavarivanje toplenjem [12].

Od legura za plastičnu preradu koristi se legura AA 5754 (AlMg3), poznata za primenu u automobilskoj industriji i za hermetička kućišta u industriji elektronike. Aluminijum - magnezijum legura AA 5754 ima izrazito visoku otpornost ka oksidaciji i koroziji. Ona se primenjuje za sudove pod pritiskom, rezervoare, vozila i za izradu plovila.

Legura 6082-T6 iz serije aluminijumskih legura 6xxx ima glavne legirajuće elemente Mg i Si. Zbog njene visoke otpornosti na naponsku koroziju često se koristi kao konstrukcioni material za različite komponente u auto industriji, izradu postrojenja i za izradu plovila [13]. Ove legure mogu da se anodiziraju, naročito kada je potrebna, visoke čvrstoće i na koroziju otporna površina. U čvrsto anodiziranom stanju idealna je za kočione sisteme, elektronske ventile i klipove [2]. Takođe važan uticaj na ponašanje prema pojavi prslina, je hemijski sastav osnovnog metala. Legura 6082 (AlSi1MgMn) ima veću osetljivost na pojavu prslina pri očvršćavanju nego druge Al-Mg-Si legure [14]. Razlog je prisustvo Mg (0.75 zapr. %) i Si (0.86 zapr. %) u leguri, što objašnjava njihovu visoku osetljivost [9]. Pored toga sastav i raspodela međudedritnog rastopa pri očvršćavanju jako utiče na tendenciju stvaranja prslina umajući u vidu da su prsline usled očvršćavanja obično rezultat cepanja taking into account that solidification cracking usually results from a tearing of the interdendritic, liquid film of the remaining melt [13].

Aluminium alloy 7075 is a heat treatable aluminium alloy based on Al-Mg-Zn system. It provides a good strength and toughness after the precipitation hardening heat treatment (solution heat treatment, followed by the rapid quenching and then artificial ageing) because of the high alloy content (5-6 wt % Zn, 2-3 wt % Mg and 1-2 wt % Cu) [7]. 7075 (AlZn5.5MgCu) is an aluminium alloy with zinc as the primary alloying element (according to EN 485-2 standard) [7]. The severe HAZ softening, the cracking in the weld and the material lose by vaporisation are the major problems encountered in the 7075-aluminium alloy during fusion welding. Among other problems, the high crack susceptibility and degradation of properties in the heataffected zone (HAZ) often occur in either fusion welding (electric arc and laser welding for example) or in friction stir welding [15-16]. The 7075 aluminium alloys are used in various auto bodies because of its high specific strength, low quench sensitivity, wide range of solution heat treatment temperatures and rapid natural aging characteristics. The 7075 aluminium alloys are used in body panels, brake housings, brake pistons, air deflector parts, and seat slides [17]. Rajkumar et al. [18] report that the welding of AA 7075 by fusion welding causes solidification cracking at the heat affected zone due to presence of copper [19]. Furthermore, oxidation and/or vaporization of zinc during the welding revealed many defects such as porosity, lack-offusion, and hazardous fumes.

The remarkable positive property of this aluminium alloy is the self-hardening effect thanks to the supersaturated solid solution after air cooling (the solid solution is supersaturated even in slow cooling), then the natural ageing can occur in a couple of months. This characteristic can be advantageous in terms of the production of welded structures, since the acceptably strength can be partially realized without post weld ageing, however this alloy tends to intergranular corrosion [20]. This new generation of aluminium alloys is widely used in luxury cars (frame structure, brake housing, spoilers etc.) due to their comparative strength to medium strength steels. In Fig. 2 the high strength aluminium alloys in a car-body of a sport car are marked by blue colour.

međudendritnog, tečnog filma zaostalog rastopa [13].

Legura aluminijuma 7075 je termički obradljiva aluminijumska legura zasnovana na sistemu Al-Mg-Zn. Ona obezbeđuje dobru čvrstoću i žilavost posle termičkog tretmana - precipitacionog ojačavanja (žarenje praćeno brzim kaljenjem i zatim veštačkim starenjem), naročito zbog visokog sadržaja legirajućih elemenata (5-6 zapr. % Zn, 2-3 zapr. % Mg i 1-2 zapr. % Cu) [7]. Legura aluminijuma 7075 (AlZn5.5MgCu) prema standard EN 485-2 je primarno legirana cinkom [7]. Izrazito omekšavanje ZUTa, prsline u metalu šava i gubitak materijala usled isparavanja su glavni problemi koji se javljaju u aluminijumskoj leguri 7075 tokom zavarivanja topljenjem. Pored ostalog, visoka osetljivost na prsline i degradacija osobina u zoni uticaja toplote (ZUT) se često javljaju pri zavarivanju topljenjem, kao što su elektrolučno ili lasersko zavarivanje ili zavarivanje trenjem sa mešanjem [15-16]. Aluminijumska legura 7075 se primenjuje za izradu vozila zbog njene visoke specifične čvrstoće, male osetljivosti na zakaljivanje i širokog opsega temperatura žarenja i karakteristike brzog prirodnog starenja. Legura se koristi za panele karoserije vozila, kućišta kočnica, kočione klipove, delove usmerivača vazduha i klizače za sedišta [17]. Rajkumar i dr. [18] su pokazali da zavarivanje topljenjem legure AA7075 izaziva prsline usled očvršćavanja u zoni uticaja toplote zbog prisustva bakra [19]. Takođe oksidacija i/ili isparavanje cinka za vreme zavarivanja izaziva mnoge greške kao što je poroznost, neprovar i oslobađa pri zavarivanju otrovna isparenja.

Značajna pozitivna osobina ovih aluminijumskih legura je efekat samoojačavanja zahvaljujući stvaranju prezasićenog čvrstog rastvora posle hlađenja na vazduhu (čvrsti rastvor je prezasićen čak i pri sporom hlađenju), tako da se prirodno starenje obavlja tokom nekoliko meseci. Ova karakteristika predstavlja prednost pri proizvodnji zavarenih konstrukcija, pri čemu se prihvatljiva čvrstoća može delimično postići bez starenja posle zavarivanja, međutim ova legura ima tendenciju intergranularne korozije [20].

Ova nova generacija aluminijumskih legura se široko primenjuje kod luksuznih kola (konstrukcija rama, kliješta kočnica, spojleri i dr.) zbog njihove čvrstoće koja je uporedljiva sa čvrstoćom srednje čvrstih čelika. Na Slici 2 prikazana je primena aluminijumskih legura visoke čvrstoće za izradu delova karoserija sportskih kola i označeni su svetlo sivom bojom.

Figure 2. *High strength aluminium alloys in a sport car-body [21]*
Slika 2. *Aluminijumske legure visoke čvrstoće u karoserijama sportskih automobila [21]*

3. Experimental plan

The increasing utilization of aluminium alloys can be originated to their low density, good heat and electric conductivity

3.1 Investigated material

The material investigated was a commercial 5754-H22, 6082-T6 with a thickness of 1 mm & 7075-T6 with a thickness of 1.5 mm and the sheet were cut in the rolling direction. Since the experimental 7075-T6 alloy under development by the material producer and it has not been available in the market yet, just the typical chemical composition and mechanical properties are presented. The chemical composition and mechanical properties of these aluminium alloys are shown in Tab. 1 and Tab. 2 respectively. The chemical composition of the investigated aluminium alloys in mass percent is summarized in Table 1.

3. Eksperimentalni plan

Povećana primena aluminijumskih legura proističe iz njihove male gustine, dobre toplotne i električne provodljivosti.

3.1 Ispitivani materijal

Materijal za ispitivanje je bio komercijalna legura 5754-H22, 6082-T6, debljine 1 mm i legura 7075-T6 debljine 1.5 mm u obliku traka koje su isečene u pravcu valjanja. Pošto je eksperimentalna legura 7075-T6 još uvek u razvoju kod proizvođača i nije još uvek na tržištu, prikazani su tipičan hemijski sastav i mehaničke osobine. Hemijski sastav i mehaničke osobine ovih aluminijumskih legura su prikazani u Tabelama 1 i 2. Hemijski sastav u masenim procentima prikazan je u Tabeli 1.

Table 1. *Typical chemical composition of aluminium alloy (wt%)*
Tabela 1. *Karakteristični hemijski sastav aluminijumskih legura (zapr. %)*

Al alloys	Cu	Fe	Mn	Cr	Mg	Ti	Si	Zn	Al
5754-H22	0.05	0.29	0.35	0.009	2.79	0.016	0.19	0.03	Bal.
6082-T6	0.09	0.46	0.40	0.02	0.70	0.03	0.90	0.08	Bal.
7075- T6	1.2-2.0	≤0.5	≤0.3	0.18-0.28	2.1-2.9	≤0.2	0.4	5.1-6.1	Bal.

The typical mechanical properties of aluminium alloys are presented in Tab. 2.

Mehaničke osobine aluminijumskih legura prikazane su u Tabeli 2.

Table 2. *Typical mechanical properties of aluminium alloy*
Tabela 2. *Karakteristične mehaničke osobine aluminijumskih legura*

Al alloys	Rm, MPa	$Rp_{0.2}$, MPa	A_{50}, %	$HV_{0.2}$
5754-H22	220	137	22	71
6082-T6	280	315	12	107
7075-T6	572	513	14	180

3.2 Physical simulation

During the planning of the experiments our aim was to analyse the heat-affected zone (HAZ) in terms of softening during Gas Tungsten Arc Welding. To investigate the weldability of 5754-H22, 6082-T6, 7075-T6 aluminium alloys, tests were designed to simulate the material properties at different peak temperatures using the Gleeble 3500 simulator. The Gleeble recreates specific sections of the HAZ based on the programmed thermal cycle [22]. HAZ properties can be limitedly analysed by conventional material tests, therefore physical simulators (i.e. Gleeble) were developed for the examination of different HAZ areas [23,24-25] During the experimental work, HAZ tests have been performed in a new generation thermophysical simulator, called Gleeble 3500, installed in the Institute of Materials Science and Technology of the University of Miskolc as shown in Fig. 3.

3.2 Fizička simulacija

Planiranje eksperimenata imalo je za cilj da analizira zonu uticaja toplote (ZUT) i njeno omekšavanje za vreme elektrolučnog zavarivanja u zaštitnoj atmosferi sa volframovom elektrodom. Da bi se ispitala zavarljivost aluminijumskih legura 5754-H22, 6082-T6 i 7075-T6, ispitivanja su osmišljena da simuliraju osobine materijala na različitim vršnim temepraturama primenom Gleeble 3500 simulatora. Uređaj Gleeble menja pojedine delove ZUTa na osnovu programiranog termalnog ciklusa [22]. Osobine ZUTa mogu ograničeno da se analiziraju klasičnim ispitivanjima materijala, što je razlog razvoja fizičkih simulatora (na pr. Gleeble) za ispitivanje različitih oblasti ZUTa [23, 24-25]. Tokom eksperimentalnog rada, ispitivanja ZUTa vršena su na novoj generaciji termofizičkih simulatora, nazvanih Gleeble 3500 (Slika 3), koji je instaliran na Institutu za nauku o materijalima i tehnologijama Univerziteta u Miskolcu.

Figure 3. *Gleeble 3500 simulator system*
Slika 3. *Sistem simulatora Gleeble 3500*

Due to its direct resistance heating system the achievable heating rate can be as high as 10 000 °C/s, whilst the cooling rate can be similarly high. Although it must be remarked that the heating and cooling rate are always the function of specimen size and shape, and in many cases external cooling is needed for the desired cooling rate.

3.3 Heat source model

In the Quicksim software developed for Gleeble programming the possible HAZ simulation welding heat cycle models are F (s, d) thermocouple measurement or FEM, Hannerz, Rykalin-2D, Rykalin-3D, Rosenthal, Exponential. But in this paper, heat cycles were determined according to the Rykalin 2D model by considering the 1 mm & 1.5 mm sheet thickness. This model describes the temperature field generated by a moving spot-like heat source on the surface of a semi infinity body. In the sheet metals the characteristic roll of heat

Zbog direktnog otpornog sistema zagrevanja, može se ostvariti brzina zagrevanja do 10.000 °C/s, dok brzina hlađenja može biti takođe velika. Mora se naglasiti da brzine zagrevanja i hlađenja su uvek u funkciji veličine i oblika uzorka i često je potrebno spoljnje hlađenje da bi se ostvarila željena brzina hlađenja.

3.3 Model izvora toplote

Za simulacije ZUTa razvijen je softver Quicksim za programiranje uređaja Gleeble. Modeli toplotnog ciklusa izvora toplote, mogu biti F(s,d) zasnovani na merenjima termoparovima ili proračunima metodom FEM, zatim modelima Hannerz-a, Rykalina 2D, Rykalina 3D, Rosenthal-a i eksponencialni. U ovom radu za toplotni ciklus definisan je Rikalin-ovim 2D modelom i razmatrana je traka debljine 1 mm i 1.5 mm. Po ovom modelu temperaturno polje se generiše kretanjem toplotnog izvora u obliku tačke na površini polubeskonačnog conduction disappears and the roll of convection is getting more important due to the larger surface to volume ratio. By the application of Rykalin 2D model the time-temperature points of HAZ heat cycle can be calculated as follows (QuikSimTM Software) [26]:

tela. U simuliranoj metalnoj traci karakteristični udeo provođenja toplote se zanemaruje, a udeo toplote zračenja postaje značajan zbog većeg odnosa površina prema zapremini zamišljenog tela koje se zavaruje. Primenom Rikalin 2D modela u tačkama u ZUTu kao i toplotni ciklus u njima, prikazan je kroz zavisnost vreme-temperatura i može se proračunati na sledeći način QuikSimTM softverom [26]:

$$T - T_0 = \frac{a}{\sqrt{b*(t-t_0)}} \exp\left(\frac{c}{t-t_0}\right) \quad (1)$$

$$a = \frac{Q}{d} \quad (2)$$

$$b = 4\pi * k * c * \rho \quad (3)$$

$$c = -\frac{r^2}{4k/(c\rho)} \quad (4)$$

$$Q = \sqrt{\frac{4\pi k c \rho \Delta t}{1/(T_2-T_0)^2 - 1/(T_1-T_0)^2}} * d \quad (5)$$

Where:
Q = energy input, J/cm;
c = specific heat, J/g/°C;
r = density; g/cm3 ;
k = thermal conductivity, W/cm/°C;
d = plate thickness, cm;
T1, T2= temperature used to define cooling time, °C;
t0 = time at the end of preheating, s; and
Δt = cooling time from T2 to T1, s.

Gde su:
Q = unos toplote, J/cm;
c = specifična toplota, J/g/°C;
r = gustina; g/cm^3;
k = thermalna provodljivost, W/cm/°C;
d = debljina ploče, cm;
T1, T2= temperature primenjene da se definiše vreme hlađenja, °C;
t0 = vreme na kraju predgrevanja, s; i
Δt = vreme hlađenja od T2 do T1, s.

3.4 HAZ thermal cycles

By the application of HAZ test in Gleeble the desired HAZ subzone can be precisely and homogeneously created in a volume sufficient for the further material tests. The Rykalin-2D model, implemented to the GSI software of Gleeble, was used for the determination of HAZ thermal cycle by considering the 1 mm & 1.5 mm sheet thickness. The heating rate, holding time, cooling time of the thermal cycle parameters were automatically adjusted according to the given plate thickness, energy input and possible procedures during the tungsten inert gas welding. The thermophysical properties of the given alloy were used for the model. Four HAZ peak temperatures were selected in the function of the distance from the fusion line. Two linear heat input values (100 and 200 J/mm) were selected in order to simulate a low and a high heat input welding at the given sheet thickness and welding technology. The desired subzones were simulated on 4-4 samples. The programmed thermal cycles of the different HAZ subzones are illustrated in Fig. 4 and 5.

3.4 Termalni ciklus ZUTa

Primenom ispitivanja na Gleeble, željene subzone u ZUTu mogu se precizno i ravnomerno stvoriti u zapremini dovoljnoj za dalja ispitivanja materijala. Rikalin - ov 2D model, implementiran u GSI softver za Gleeble uređaj, je primenjen za određivanje temalnog ciklusa ZUTa, ramatrajući trake debljina 1 mm i 1.5 mm. Parametri termalnog ciklusa kao što su: brzina zagrevanja, vreme zadržavanja, vreme hlađenja su automatski podešavani u skladu sa debljinom ispitivane trake, unosom energije i mogućim procedurama karakterističnim za TIG zavarivanje. Termofizičke osobine ispitivanih legura su korišćene u modelu. Četiri vršnih – maksimalnih temperatura u ZUTu su izabrane u zavisnosti od rastojanja od linije spoja.
Dve vrednosti unosa toplote (100 i 200 J/mm) su izabrane u cilju simulacije niskog i visokog unosa toplote za zavarivanje ispitivane debljine trake i izabrane tehnologije zavarivanja. Planirane simulacije subzona su vršene na 4-4 uzorka. Programirani termalni ciklus različitih subzona ZUTa su ilustrovane na Slikama 4 i 5.

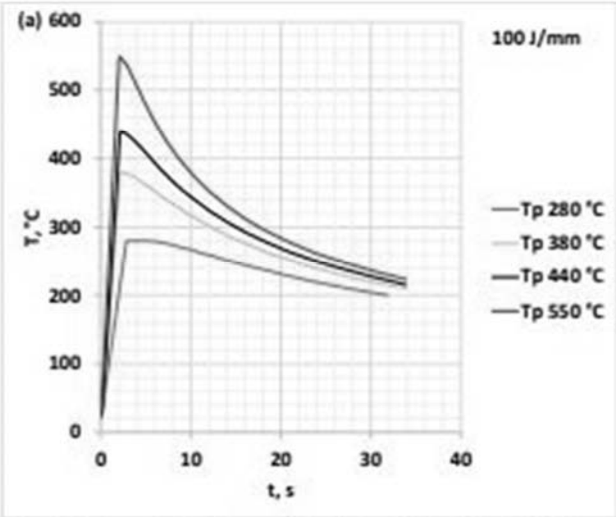

Figure 4. *HAZ thermal cycles at low heat input (100 J/mm)*
Slika 4. *ZUT termalni ciklus za nizak unos toplote (100 J/mm)*

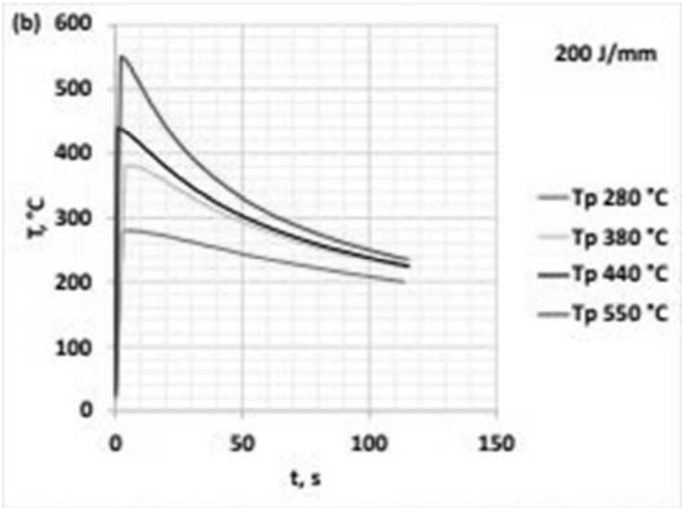

Figure 5. *HAZ thermal cycles at high heat input (200 J/mm)*
Slika 5. *ZUT termalni ciklus za visok unos toplote (200 J/mm)*

3.5 Experimental circumstances

The aluminium sheet which are used for thermomechanical testing using Gleeble 3500 simulator are short samples. A precise preparation of HAZ specimen with required geometrical shape and good surface quality is indispensable for the successful simulation. A K(NiCr-Ni) type thermocouple was welded onto the middle of sample for temperature record. During those simulations when the maximal temperature was higher than 450 °C there was a risk of the failure of thermocouples at the contacting points to the specimens. Therefore, the joints were protected by cement according to the recommendations of Gleeble manual. In Fig. 6 the applied specimens (70x10x1 mm) & (70x10x1.5 mm) are presented (left: without cement, right: with cement), whilst in Fig. 7 the test specimen is shown in the test (vacuum) chamber.

3.5 Eksperimentalni detalji

Aluminijumske trake koje su korišćene za termomehanička ispitivanja primenom Gleeble 3500 simulatora su kratki uzorci. Precizna priprema ZUT uzoraka sa zahtevanim geometrijskim oblikom i dobrim kvalitetom površine su neizostavni za uspešnu simulaciju. Termopar tipa K(NiCr-Ni) za beleženje temperatura je zavaren na sredini uzorka. Za vreme izvođenja simulacija, kada su temperature više od 450 °C, postojao je rizik kvara termopara na kontaktnoj površini uzorka. Zato su spojevi zaštićeni cementom, u skladu sa uputstvom za uređaj Gleeble. Na Slici 6. prikazani su uzorci za ispitivanje, levo bez zaštite kontakta cementom, a desno sa cementnom zaštitom. Na Slici 7. prikazan je ispitni uzorak u ispitnoj (vacuum) komori.

Figure 6. *Specimens for the physical simulations*
Slika 6. *Uzorci za fizičku simulaciju*

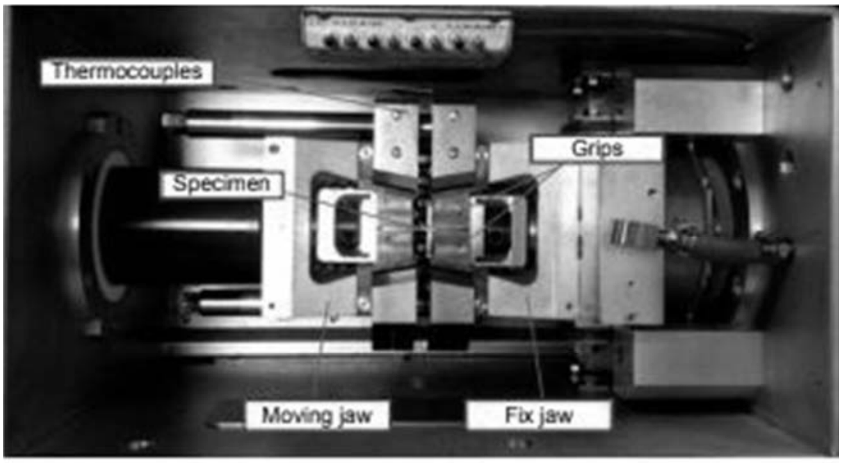

Figure 7. *Specimen in the test chamber*
Slika 7. *Uzorak u ispitnoj komori*

4. Characterization of HAZ softening

The desired HAZ areas (550 °C, 440 °C, 380 °C, 280 °C) were successfully simulated for two relevant linear heat input values during the experiments. After the successful simulations the specimens were perpendicularly cut at thermocouples and hardness test were elaborated. The results of Vickers hardness test, which was performed by a Mitutoyo MVK-H1 microhardness tester with HV0.2 load, are summarized in Fig. 8 and Fig. 9.

4. Karakterizacija omekšavanja ZUTa

Planirane oblasti ZUTa (550 °C, 440 °C, 380 °C, 280 °C) su uspešno simulirane tokom eksperimenta, za dve vrednosti unosa toplote. Posle uspešne simulacije uzorci su poprečno odsečeni na mestima termoparova i izvršena su ispitivnja tvrdoća. Rezultati ispitivanja Vikers tvrdoće, koji su izvršeni na uređaju za ispitivanje mikrotvrdoće Mitutoyo MVK-H1, sa opterećenjem od HV0.2 su prikazani na Sikama 8 i 9.

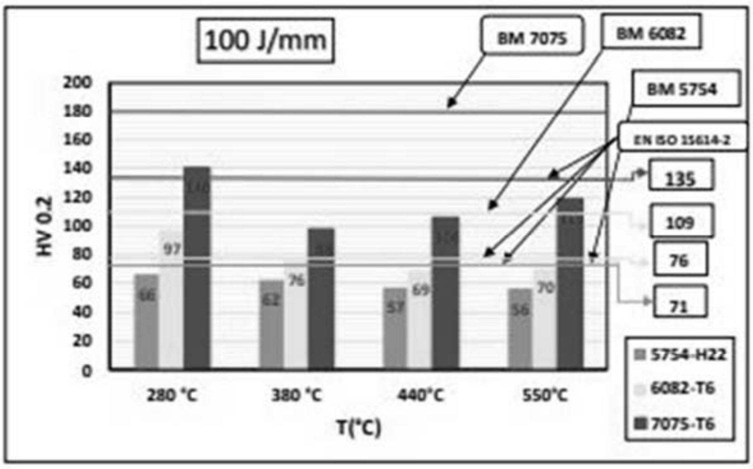

Figure 8. *Hardness distribution in HAZ at different linear heat inputs*
Slika 8. *Raspodela tvrdoća u ZUTu za različite unose toplota*

Although according to the governing standard for the qualification of welding procedure (EN ISO 15614-2) there is not any requirement for the maximum or minimum hardness of the aluminium welded joint, the strength level can be characterized by the hardness, since there is a correlation between the hardness and the strength.

Standardom za kvalifikaciju procedura zavarivanja (EN ISO 15614-2), nisu definisani zahtevi za najveću ili najnižu tvrdoću zavarenih spojeva aluminijuma. Nivo čvrstoće može se orediti na osnovu tvrdoće, obzirom da postoji korelacija između tvrdoće i čvrstoće.

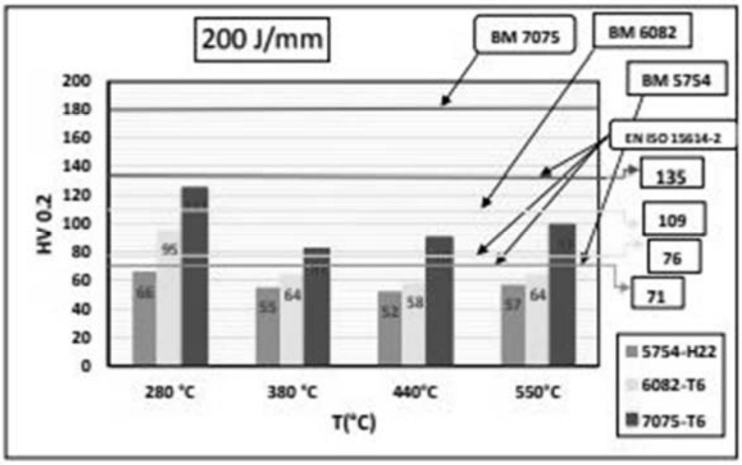

Figure 9. *Hardness distribution in HAZ at different linear heat inputs*
Slika 9. *Raspodela tvrdoća u ZUTu za različite unose toplote*

The examined AA5754-H22, AA6082-T6 & AA7075-T6 aluminium alloy belongs to the 22.3, 23.1 & 23.2 group respectively of CR ISO 15608, which means that the requirement for the tensile strength of the welded joint is the 100%, 70% & 75% respectively of the base material according to EN ISO 15614-2. If we consider the same requirement for the HAZ hardness compared to the base material, the hardness should reach 71 HV0.2, 76 HV0.2 & 135 HV0.2 in HAZ when the 5754-H22, 6082-T6 & 7075-T6 base material has 71 HV0.2, 109 HV0.2 & 180 HV0.2 respectively.

It can be seen from HAZ simulation results that for 5754- H22 aluminium alloy with the increase of the linear heat input the hardness of the heat affect zone has decreased further in the case of the transversally tested specimens. Using 100 J/mm linear heat input, test specimens with slightly higher hardness were obtained than with linear heat input of 200 J/mm. However, the difference between the test pieces tested with the same peak temperature simulation is minimal. Basically, with the use of both linear heat input, the simulated peak temperature 440 °C was the most critical, while the most favourable values were produced with the peak temperature 280 °C. In both cases, the hardness of the 280 °C peak temperature thermal cycle was at a level of compliance of 90%, significantly closer to the original hardness of the base material, but in other cases it was not achieved. All simulated sub zone hardness is below the prescribed limit according to EN ISO 15614-2.

Ispitivane legure AA5754-H22, AA6082-T6 i AA7075-T6 pripadaju grupi 22.3, 23.1 i 23.2 prema standardu CR ISO 15608, što znači da zahtevi za zateznom čvrstoćom zavarenih spojeva su 100%, 70% i 75% od osnovnog materijala, a u skladu sa standardom EN ISO 15614-2. Ako se posmatraju isti zahtevi za tvrdoćama u ZUTu, u poređenju sa osnovnim materijalom dobijaju se vrednosti od : 71 HV0.2, 76 HV0.2 i 135 HV0.2 u ZUTu dok osnovni material legura 5754-H22, 6082-T6 i 7075-T6 ima vrednosti tvrdoća od: 71 HV0.2, 109 HV0.2 i 180 HV0.2.

Iz rezultata simulacije ZUTa za aluminijumsku leguru 5754-H22 se može videti da sa povećanjem linearnog unosa toplote, tvrdoća zone uticaja toplote opada i u slučaju uzdužno ispitivanih uzoraka. Primena linearnog unosa toplote od 100 J/mm, dobijeni su uzorci sa neznatno višom tvrdoćom nego sa linearnim unosom toplote od 200 J/mm. Međutim, minimalna je razlika između uzoraka ispitnih na istoj vršnoj temperaturi. U osnovi, primenom oba linearna unosa toplote, simulirana vršna temperatura od 440 °C je najkritičnija, dok su najpovoljnije vrednosti dobijene sa vršnom temperaturom od 280 °C. U oba slučaja tvrdoća dobijena termalnim ciklusom na temperaturi od 280 °C je na nivou od oko 90%, što je značajno bliže originalnoj tvrdoći osnovnog materijala, ali u drugim slučajevima nije dostignuto. Tvrdoće svih simuliranih subzona su ispod zahtevanih prema standardu EN ISO 15614-2.

In case of 6082-T6 aluminium alloy, sub zones have always been softened by the applied linear heat input, and with the increase of linear heat input, the hardness of the heat affected zone has further decreased. However, in different zones heated to different temperatures there was a markedly different degree of softening. In addition, the positive conclusion is that the hardness of the examined peak temperatures in three cases reached the hardness expected by the standard, and two times exceeded the 90% of the requirement value. Compared to the results of the 5754-H22, it can be clearly established that the aluminium alloy 6082- T6 reacts more favourably to the linear heat inputs of the different peak temperature simulated zone. The reduction in hardness of the 6082-T6 aluminium alloy is due to the deterioration in the quality of the constituents originally present in the base material. This negative change can be due to over-regeneration, which occurs in zones that are too high at peak temperatures and cause precipitation to develop. Thus, the hardness distribution of the heat affect zone depends on the interaction between solubility and recrystallization.

It can be clearly seen from simulated 7075-T6 aluminium alloy, welding has significantly softened it. The hardness following the simulation, with one exception, is below the standard hardness. In terms of linear heat input, it can be clearly established that the 100 J/mm linear heat input is more favourable than 200 J/mm in terms of maintaining the strength properties. By the increase of the linear heat input the hardness distribution was even lower. However, using higher linear heat input makes the process more productive. The amount of softening was the most critical at the 380 °C peak temperature subzone.

It can be concluded that the hardness was lower almost in all peak temperatures and heat inputs. However, it can be important to note that the total strength of the welded joint is not only determined by the strength of the weakest point, since the width of softened zones should be also considered.

4.1 Materials tests

Optical microscopic tests were performed in 200x magnification by a Zeiss Axio Observer D1m. The samples were etched by Barker-etching (5 g HBF4 + 200 ml water) which is recommended for aluminium alloys. During this process an oxide layer forms on the surface. This optically active oxide forms with diverse speed on the different orientation grains, therefore by the application of polarized light the grains have different colour in the

U slučaju aluminijumske legure 6082-T6, subzone su omekšale za svaki od unosa toplote i sa povećanjem linearnog unosa toplote tvrdoća zone uticaja toplote je i dalje omekšavala. Međutim, u različitim zonama koje su zagrevane do različitih temperatura, dešavao se različit stepen omekšavanja. Kao pozitivan zaključak može se reći da tvrdoća za ispitivane vršne temperature su u tri slučaja postigle vrednosti u skladu sa standardom, a u dva slučaja pokazuju 90 % od zahtevanih vrednosti. Poredeći sa rezultatima legure 5754-H22 može se ustanoviti da aluminijumska legura 6082-T6 reaguje mnogo povoljnije na linearni unos toplote za različite vršne temperature u simuliranoj zoni. Smanjenje tvrdoće aluminijumske legure 6082-T6 se dešava zbog snižavanja kvaliteta mikrokonstituenata koji su primarno prisutni u osnovnom materijalu. Ove negativne promene mogu nastati zbog ponovne regeneracije, koja se dešava u zonama koje su na visokim temperaturama i omogućavaju proces taloženja. Na osnovu toga, raspodela tvrdoća u zoni uticaja toplote zavisi od međudejstva između rastvorljivosti i rekristalizacije.

Iz simulacije aluminijumske legure 7075-T6 može se jasno videti da je zavarivanje značajno omekšava. Tvrdoća je nakon simulacije, sa jednim izuzetkom, ispod standardnih vrednosti za tvrdoću. Razmatrajući linearni unos toplote, može se jasno utvrditi da je unos toplote od 100 J/mm mnogo povoljniji nego unos od 200 J/mm za održanje nivoa osobina čvrstoće. Povećanjem unosa toplote, raspodela tvrdoće je čak niža. Međutim, primena većeg linearnog unosa toplote čini proces mnogo produktivnijim. Udeo omekšavanja je najkritičniji na vršnoj temperaturi od 380 °C.

Može se zaključiti da je tvrdoća bila niža za skoro sve vršne temperature i unose toplote. Međutim, važno je napomenuti da ukupna čvrstoća zavarenog spoja nije samo određena čvrstoćom najslabijih tačaka, obzirom da bi trebalo da se uzme u obzir širina omekšale zone.

4.1 Ispitvanje materijala

Mikroskopska ispitivanja vršena su na optičkom mikroskopu Zeiss Axio Observer D1m, pri uvećanju 200 puta. Uzorci su nagrizani u rastvoru Barker (5 g HBF4 + 200 ml vode), koji je preporučen za aluminijumske legure. Za vreme ovog procesa oksidni film se formira na površini. Ovaj optički aktivan oksidni sloj formira se različitim brzinama na različito orjentisanim zrnima, tako da primenom polarizovanog svetla zrna imaju različitu boju u zavisnosti od njihove orijentacije.

function of their orientation. The grain structure of the investigated subzone for AA5754-H22, AA6082-T6 & AA7075-T6 aluminium alloys at the different peak temperatures (550 °C, 440 °C, 380 °C, 280 °C) and linear heat input 200 J/mm were illustrated in Fig. 10a,b,c-d, Fig. 11a,b,c-d and Fig. 12a,b,c-d respectively at M=200x. In Figure 10a, we can see that grains are spherical and bigger and getting refined at lower peak temperature (Figure 10d) thus imparting high hardness compared to other peak temperatures. Similarly, in case of Fig. 11a and 11c have identical microstructure and giving the same hardness but in Fig. 11b grains are broader and also this simulated zone (T=280 °C) observed as more critical. In the Fig. 12d, can be observed as very fine, elongated grains thus at the peak temperature of 280 °C has highest hardness as compared to others which can be correlated to this figure.

Mikrostrukture ispitivanih subzona za aluminijumske legure AA5754-H22, AA6082-T6 i AA7075-T6, za različite vršne temperature (550 °C, 440 °C, 380 °C, 280 °C) i linearni unos toplote od 200 J/mm, su prikazane na Slikama 10a,b,c-d, Slikama 11a,b,c-d i Slikama 12a,b,c-d, pri uvećanju od 200 puta. Na slici 10a se može videti da su zrna sferična i veća i postaju rafinisanija na nižim vršnim temperaturama (Slika 10d), tako da daju visoku tvrdoću u poređenju sa ostalim vršnim temperaturama. Slično u slučaju na Slikama 11a i 11c prikazuju se identične mikrostrukture i koje daju istu tvrdoću. Na Slici 11b zrna su šira i za tu simuliranu zonu (T=280 °C) je primećeno da je mnogo kritičnija. Na Slici 12d, mogu se videti vrlo fina, izdužena zrna, tako da na vršnoj temperaturi od 280 °C, imaju najvišu tvrdoću u poređenju sa drugim koje se mogu uporediti sa ovom slikom.

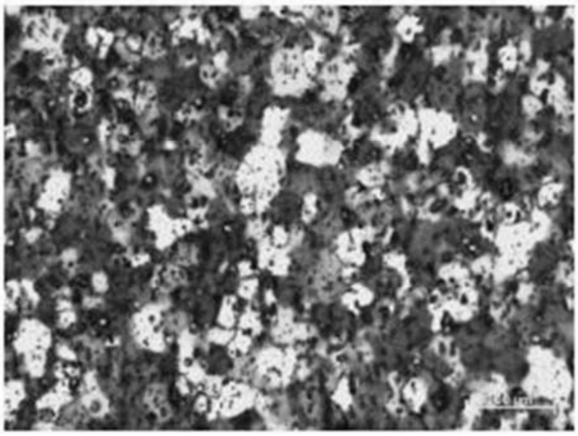

***Figure 10 (a)** T= 550 °C, Linear heat input 200 J/mm*
***Slika 10 (a)** T= 550 °C, Linearni unos toplote 200 J/mm*

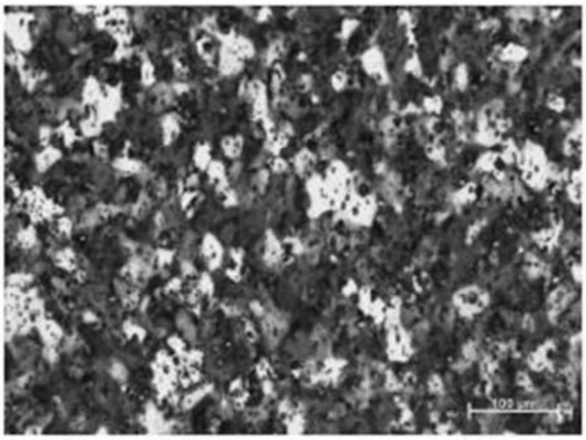

***Figure 10 (b)** T= 440 °C, Linear heat input 200 J/mm*
***Slika 10 (b)** T= 440°C, Linearni unos toplote 200 J/mm*

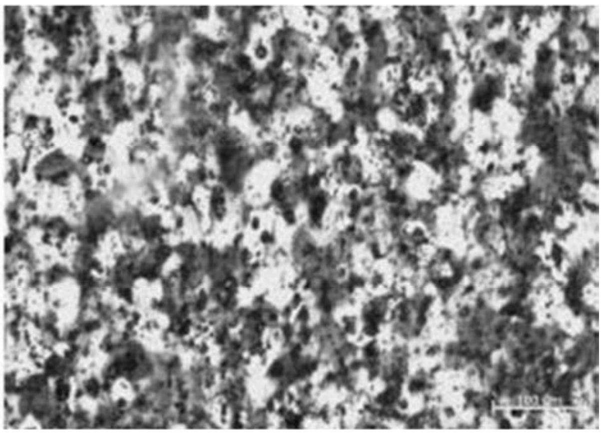

***Figure 10 (c)** T= 380 °C, Linear heat input 200 J/mm*
***Slika 10 (c)** T= 380 °C, Linearni unos toplote 200 J/mm*

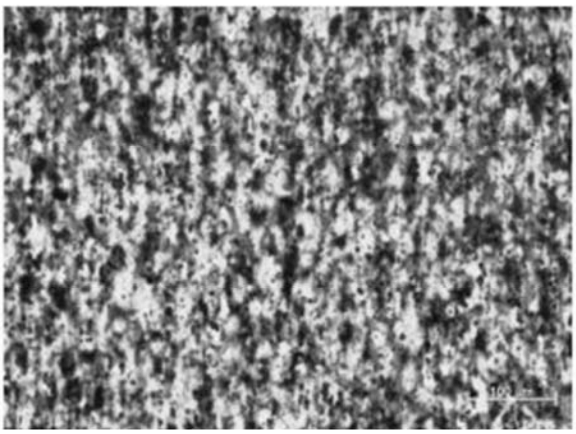

***Figure 10 (d)** T= 280 °C, Linear heat input 200 J/m*
***Slika 10 (d)** T= 280 °C, Linearni unos toplote 200 J/mm*

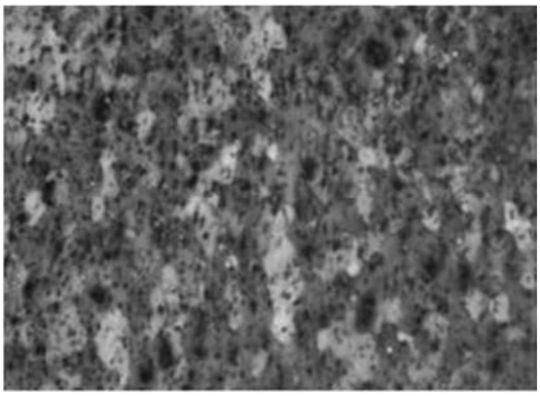

***Figure 11 (a)** T= 550 °C, Linear heat input 200 J/mm*
***Slika 11 (a)** T= 550 °C, Linearni unos toplote 200 J/mm*

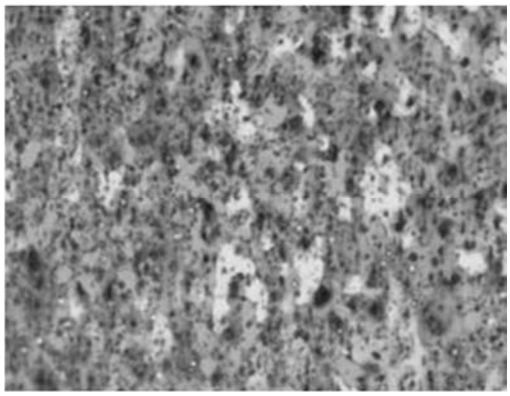

***Figure 11 (b)** T= 440 °C, Linear heat input 200 J/mm*
***Slika 11 (b)** T= 440°C, Linearni unos toplote 200 J/mm*

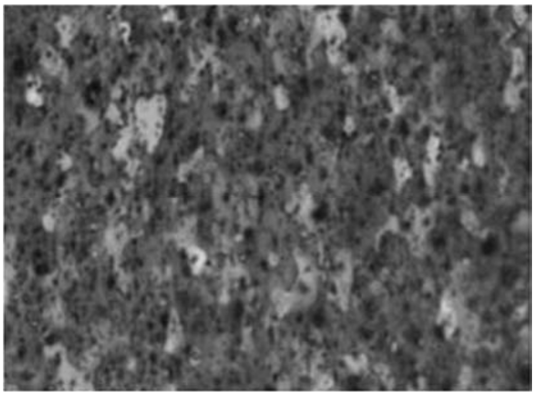

***Figure 11 (c)** T= 380 °C, Linear heat input 200 J/mm*
***Slika 11(c)** T= 380 °C, Linearni unos toplote 200 J/mm*

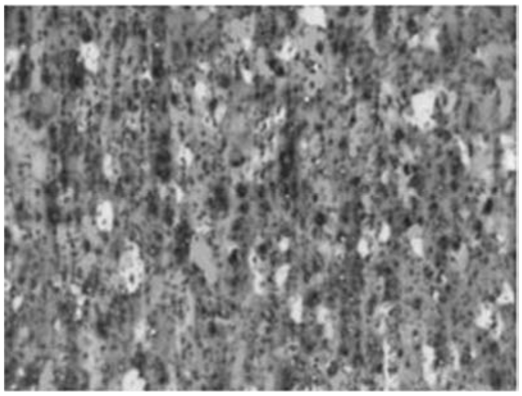

***Figure 11 (d)** T= 280 °C, Linear heat input 200 J/mm*
***Slika 11(d)** T= 280 °C, Linearni unos toplote 200 J/mm*

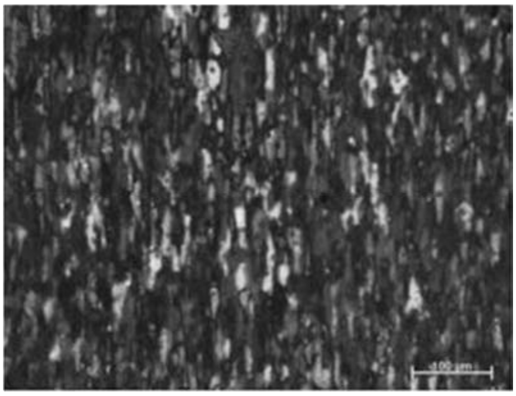

***Figure 12 (a)** T= 550 °C, Linear heat input 200 J/mm*
***Slika 12 (a)** T= 550 °C, Linearni unos toplote 200 J/mm*

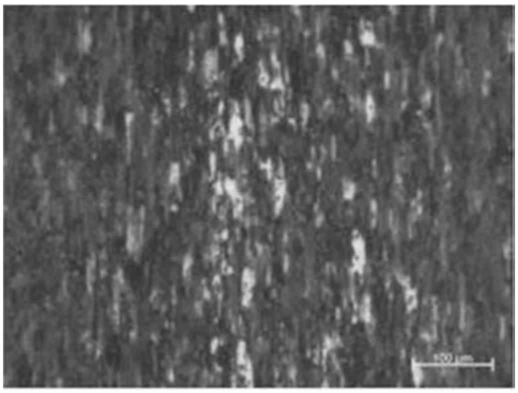

***Figure 12 (b)** T= 440 °C, Linear heat input 200 J/mm*
***Slika 12 (b)** T= 440°C, Linearni unos toplote 200 J/mm*

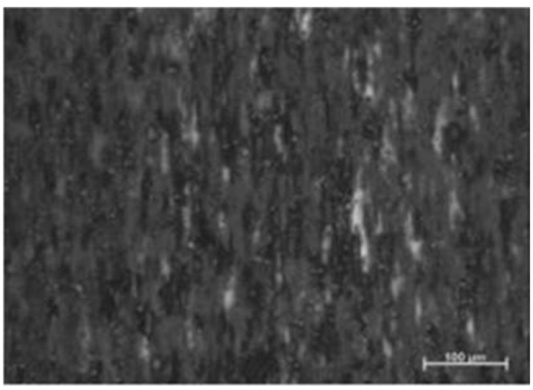

***Figure 12 (c)** T= 380 °C, Linear heat input 200 J/mm*
***Slika 12 (c)** T= 380 °C, Linearni unos toplote 200 J/mm*

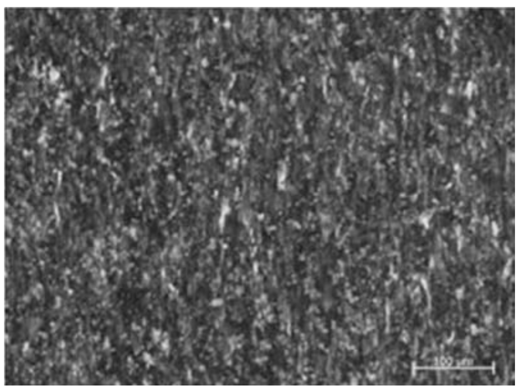

***Figure 12 (d)** T= 280 °C, Linear heat input 200 J/mm*
***Slika 12 (d)** T= 280 °C, Linearni unos toplote 200 J/mm*

From the diagram it can be concluded that at lowest simulated peak temperature hardness is higher, but softening can be observed at higher simulated peak temperature, however the measured values are still under the derived requirement.

Iz dijagrama se može zaključiti da pri nižim simuliranim vršnim temperaturama, tvrdoća je viša, ali omekšavanje se može uočiti.
Na višim simuliranim vršnim temperaturama, ipak merene vrednosti su i dalje ispod postavljenih zahteva.

5. Summary and conclusions

The reproduction of heat affected zone areas during the TIG welding of 5754-H22, 6082-T6 and 7075-T6 alloy were successfully performed, using the Rykalin 2D model in the Gleeble 3500 physical simulator. Two technological variants (Q = 100 J/mm and 200 J/mm, linear heat input) and four peak temperatures 550 ºC, 440 ºC, 380 ºC and 280 ºC were selected.

Based on the performed simulations and hardness tests the most critical subzone in terms of softening has been identified was the most critical 440 °C for 5754-H22, 6082- T6 and 380 ºC for 7075-T6. It can be seen from HAZ simulation results that for 5754-H22 aluminium alloy with the increase of the linear heat input the hardness of the heat affect zone has decreased further. In case of 6082-T6 aluminium alloy, sub zones have always been softened by the applied linear heat input, and with the increase of linear heat input, the hardness of the heat affected zone has further decreased. We concluded that the hardness was under the derived requirement in all investigated subzones, however by the reduction of linear heat input from 200 J/mm to 100 J/mm the hardness (and therefore the strength) can significantly increase in case of 7075-T6. The performed optical microscopic tests verified that the demanded subzones were successfully created during the physical simulation.

5. Zakjučci

Reprodukovanje pojedinih oblasti zone pod uticajem toplote za vreme TIG zavarivanja aluminijumskih legura 5754-H22, 6082-T6 i 7075-T6, je uspešno izvedeno primenom Rikalinovog 2D modela na Gleeble 3500 fizičkom simulatoru. Ispitivane su dve tehnološke variante linearnog unosa toplote (Q = 100 J/mm i 200 J/mm) i bile su izabrane četiri vršne temperature 550 ºC, 440 ºC, 380 ºC i 280 ºC.
Na osnovu izvršenih simulacija i merenja tvrdoća, identifikovane su najkritičnije subzone u pogledu omekšavanja. Najkritičnije za legure 5754-H22 i 6082-T6 je temperatura od 440 °C, a temperatura od 380 ºC za leguru 7075-T6. Može se videti iz rezultata simulacije ZUTa, da kod aluminijumske legure 5754-H22 sa povećanjem linearnog unosa tolote, tvrdoća zone uticaja toplote opada. U slučaju aluminijumske legure 6082-T6, subzone su uvek omekšavale, sa svakim od primenjenih unosa toplote i da sa povećanjem linearnog unosa toplote opada tvrdoća zone uticaja toplote. Može se zaključiti da tvrdoća kod svih ispitivanih subzona, smanjenjem linearnog unosa toplote od 200 J/mm do 100 J/mm, tvrdoća kao i čvrstoća, mogu značajno da porastu u slučaju legure 7075-T6. Izvršena ispitivanja optičkom mikroskopijom su potvrdila da su planirane subzone uspešno ostvarene primenom fizičke simulacije.

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